The relationship between school science and mathematics education

Wong, Victoria Jane

Awarding institution:
King's College London

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Victoria Wong

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Abstract

Science is dependent on mathematical thinking and mathematical tools but this close and dependent relationship is frequently not reflected in schools or education policy. There have been calls in the literature for school science and mathematics departments to work together more closely for reasons including a perceived overlap of content and to improve students' use of mathematics in science. This thesis critiques these calls and questions the plausibility of such proposals. In particular, it asks:

1. How and to what extent can mathematics and science educators work together?

2. What are the barriers to effective, mutually beneficial, collaborations between mathematics and science teachers?

3. How might these barriers be addressed?

A two-phase qualitative approach was undertaken to explore participants' experiences and views of the relationship between mathematics and science education. Two distinct groups were approached and interviewed to gain insights into both the policy-making process at a national level and the realities of working in school: those influential in science and mathematics policy-making; and science and mathematics teachers collaborating in schools. The interview data were coded and analysed using thematic analysis. Different theoretical lenses were used to interrogate the data, each providing unique perspectives. They included: power and boundaries, based particularly on the writing of Bernstein; policy, using Bernstein and Ball; the notion of transfer; and the impact of beliefs and identity on curriculum decision making. The findings demonstrate that the dependency in the relationship is asymmetrical: science is dependent on mathematics, but the reverse is not true making it difficult for a truly mutually beneficial relationship to be developed as science will always tend to gain more from any collaboration. This asymmetric dependency is not discussed in other authors' work on science-mathematics collaboration but would appear to be critical in understanding why collaboration in school is rare and often short-lived.

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Chapter 1
Setting the scene: Existing at a distance from each other

1.1 Mathematics in science

It has been claimed that 'mathematics is the language of science'. It is not an uncontested notion, however, with the biology professor E. O. Wilson writing in the *Wall Street Journal* that 'many of the most successful scientists in the world today are mathematically no more than semiliterate' (Wilson, 2013). It is further notable that even those authors who counter the views expressed by Wilson acknowledge that many historical scientists, such as Michael Faraday, have known little mathematics (Marcus & Davis, 2013).

In spite of disputes about just how much mathematics one needs in order to progress in a scientific career, there is little disagreement that at least some mathematics is necessary to do science. Two of the eight practices of science identified by Osborne (2011), that now form a core element of the US Framework for K-12 Science Education (National Academies Press, 2012), are mathematical: analysing and interpreting data, and using mathematical tools. Almost 20 years earlier, Crombie (1994) identified six forms of reasoning in science, of which two are mathematical: mathematical deductive logic, and probabilistic and statistical thinking.

Mathematical reasoning and mathematical tools are thus argued to be intrinsic to science. That these two practices are distinct is important: mathematics is not simply a tool for the analysis of data, but a way of thinking and reasoning. In a later paper on the eight practices of science, Osborne changed the name of the practice from 'using mathematical tools' to 'using mathematical and computational thinking,' and discussed the importance of mathematics for clear communication in science:

> Mathematics and computational thinking are central to science enabling the representation of variables, the symbolic representation of relationships and the prediction of outcomes. As such mathematics supports the description of the material world enabling systematic representation that is the foundation of all scientific modelling and the clear communication of meaning. Thus mathematics serves pragmatic functions as a tool—that is both a communicative function, as one of the languages of science, and a structural function, which allows for logical

> deduction. Mathematics and numerical representation are the basis of all measurement in science. (Osborne, 2014, p. 187)

One might expect to see the close and dependent relationship that science has to mathematics reflected in school education and in science education research, but it does not appear to be so. Osborne argues that in schools a 'vaccination model' of mathematics is commonly adopted in which science teachers expect that students can learn mathematics elsewhere and can bring it with them into the science classroom:

> For too many teachers of science, however, mathematics is not something that is central and core to practice of science. Many, perhaps, operate with the vaccination model of mathematics […] that it is not their responsibility to educate students in the mathematics […] required to understand science. And if students have not been vaccinated, there is little that they, the teacher, can do. But if mathematics is not a core feature of what happens in science classrooms the nature of science will be misrepresented. Avoiding the opportunity to use mathematical forms and representations is a failure to build students [*sic*] competency to make meaning in science. (Osborne, 2014, p. 187)

In other words, mathematics is important to science but this importance is not made manifest in science education in schools. Moreover, Osborne argues that many teachers may consider mathematics as a vaccination which students receive elsewhere, and so do not regard support for mathematical content as their responsibility.

A number of authors have identified that students do have difficulty in using mathematics in science, both at school level (for example: Dodd & Bone, 1995; Porkess, 2013; Needham, 2016) and at university level (for example: Watters & Watters, 2006; Koenig, 2011; Hoban, Finlayson, & Nolan, 2013; Grove & Pugh, 2015). However, aside from identifying that students have difficulties, mathematics in science is apparently largely ignored in education research. In a comprehensive review of mathematics and science education, Orton and Roper concluded that 'the international science education research journals contain little on the science and mathematics issue' (2000, p. 143). Similarly, equally little attention is paid to the relationship in the mathematics education literature (*ibid*.). Furthermore, of the 96 chapters of the *Second International Handbook of Science Education* (Fraser, Tobin, & McRobbie, 2012), the latest edition, not one focuses on mathematics or numeracy in science; in comparison there are six on literacy in science and four on argumentation.

While there have been calls in the literature for science and mathematics departments in schools to work together more closely (for example: Dodd and Bone, 1995; Orton and Roper, 2000; Osborne, 2011; Ross, Lakin, McKechnie, and Baker, 2015; Lyon, 2016), there appears to be limited research about the impacts of closer working. For example:

> There is little research on […] whether more explicit connections or integration across the disciplines significantly improves student learning, retention, achievement, or other valued outcomes. (Honey, Pearson, & Schweingruber, 2014, p. 22)

Osborne also identifies a lack of research and argues that:

> Science and mathematics education exist at a distance from each other – the two communities rarely engage and there is an absence of a literature that explores how they could work symbiotically. (Osborne, 2011, p. 98)

Symbiosis, from the Greek meaning *living together*, is a relationship between two species of organisms and can take a number of forms (Martin & Hine, 2014):

- Mutualism is a relationship in which both organisms benefit, to be properly considered as mutualism organisms usually have to be in close contact;
- Commensalism is a relationship where one organism benefits but although the other is not harmed it does not benefit;
- Parasitism where one organism benefits and the other is harmed;
- Facultative symbiosis is one where one organism can survive without the other;
- Obligate symbiosis is a relationship where one is needed for the other to survive.

I assume that Osborne did not intend the relationship between mathematics and science to be parasitic and thus in the discussions that follow use 'mutually beneficial' in place of his term 'symbiotic'.

Thus there have been numerous calls for departments to work together more closely, but there is limited research exploring the nature of such a venture. Given the lack of research, a study exploring the relationship between school science and mathematics education would appear to be timely. Key question areas thus include how one might describe the nature of the relationship between science and mathematics education. What are the benefits to each from a closer relationship? Or, indeed, is there possible risk of harm to one or both from closer association?

1.2 Research questions

In his justification of the practices of science, Osborne (2011) bemoaned the lack of a mutually beneficial (or symbiotic) relationship between science and mathematics education. This thesis investigates the reasons for this lack, and examines the nature of collaborations which are in existence.

Fensham (2009) argues that science education policy, and the political and cultural context of that policy, is often ignored in science education research. Consequently, the contested nature of science in the curriculum is frequently disregarded as is the interplay between stakeholders in school and beyond who determine both the nature of the science curriculum and the way in which it is enacted. Therefore, in this study I investigate the practice of collaboration in school alongside the production of science and mathematics education policy.

Specifically, this research seeks to answer the following:

1. How and to what extent can mathematics and science educators work together?
2. What are the barriers to effective, mutually beneficial, collaborations between mathematics and science teachers?
3. How might these barriers be addressed?

Inevitably, in seeking to answer these questions, other questions must be addressed first. These include:

a. What are the perceived reasons for collaborating both at the level of policy, and at the level of practice?
b. What does it mean to work in a way which is mutually beneficial?

Osborne (2011) regretted the absence of a literature which explored how mathematics and science education could work symbiotically. In the next chapter, I explore science and mathematics education policy in England over the last 25 years to set the context for the research, before reviewing in Chapter 3 the small quantity of literature concerning mathematics and science collaboration and integration which does exist to see what can be learned from previous studies.

Chapter 2
The policy context in England

In this chapter, I set out the policy context which provides the backdrop to the study. I will start by describing the composition of the science and mathematics education communities. I will then explore the writing and reforming of the National Curriculum in England before looking in more detail at mathematics in the science curriculum, and science in the mathematics curriculum. I will finish by considering the other major policy initiative impacting both mathematics and science, namely the national STEM policies. This background will enable greater understanding and appreciation of the political and cultural context of both policy decision making and practice in schools.

My focus is on government education policies and their implementation in the national context of England. Although the original National Curriculum also applied to both Wales and Northern Ireland, education policy in those nations has diverged from England in recent years. Governance of education in Scotland is independent of England. Thus in this study I use 'England' throughout for consistency, even though some of the policies I discuss also applied to Wales and Northern Ireland.

2.1 The communities

Fensham argues that 'science and its teaching is one of the most hotly contested components of the school curriculum' (2009, p. 1079) with 'multiple stakeholders presenting demands' (*ibid.*, p. 1080). In the light of this, he argues for a greater focus on those stakeholders who determine the nature of the science curriculum. Exactly who these stakeholders are and what role they play shifts with time (Ball & Junemann, 2012) but, in England, would include the broader science and mathematics education communities.

2.1.1 The mathematics education community

The Joint Mathematical Council of the United Kingdom (JMC) is the umbrella organisation for mathematics. Formed in 1963, there are 21 separate societies which are part of the JMC, including the Royal Academy of Engineers and three separate mathematics teaching organisations (JMC, 2017).

The Advisory Committee on Mathematics Education (ACME) was set up in 2002 by the JMC and the Royal Society, with the secretariat housed at the Royal Society in London. It aims to develop advice to influence mathematics education policy.

2.1.2 The science education community

The science education community is widely considered to include the learned societies for the sciences taught in school: the Institute of Physics, the (now Royal) Society of Biology and the Royal Society of Chemistry, together with the Royal Society. These have relatively well-delineated areas of expertise around the particular science that they represent and fund education projects in their respective science to a greater or lesser extent. There is one professional society for science educators, the Association for Science Education (ASE), formed in 1963, which brings together those with an interest in science education.

There are also a number of charitable trusts with an interest in science education and a history of funding large science education projects, particularly the Wellcome Trust, the Gatsby Foundation (Lord David Sainsbury's charitable foundation) and the Nuffield Foundation. From 2006 to 2015 the three subject learned societies, the ASE and the Royal Society worked together as SCORE (Science Community Representing Education) to advise those making policy decisions about science education and, like ACME, the secretariat was based at the Royal Society. In 2015 it was decided to stop using the SCORE brand and instead give policy advice from the individual organisations (SCORE, 2015).

2.2 The National Curriculum

Before the advent of the National Curriculum and GCSEs in the late 1980s, students were segregated with a minority sitting the General Certificate of Education Ordinary Level (GCE O-levels) and the majority taking lower level courses such as the CSE (Certificate in Secondary Education). It has been suggested that in the mid-1980s there were as many as 400 different courses organised by a number of examination boards on offer to 14-16 year old students in England and Wales which might be considered as 'science' (Nicolson & Holman, 2003).

Many students, however, ceased studying science altogether at age 14, and participation was strongly gendered with more boys studying physics and more girls studying biology up to age 16. As a result of the advent of the National Curriculum in 1989 and the General Certificate of Secondary Education (GCSE), first awarded in 1988, the majority of schools adopted similar science curricula at least for 14-16 year olds. These policy changes helped to increase both the numbers of students studying science up to the age of 16 and the breadth of that study. In 1984 less than half of 14-16 year old students studied two or more subjects from biology, chemistry and physics; by 2001 that figure had risen to over 90 percent with the remaining students usually studying some form of science, perhaps on a Certificate of Achievement course (Nicolson & Holman, 2003).

Unsurprisingly, opening the study of science to everyone was problematic. Although English and mathematics have been seen as essential study for all students in education since the provisions of the 1870 Education Act, there are still difficulties in providing appropriately for them all. It was inevitable that science would find similar challenges (Nicolson & Holman, 2003).

2.2.1 The first National Curriculum

In 1988 the National Curriculum Council was set up by the then Secretary of State for Education, Kenneth Baker. The first National Curriculum was written by four committees of about 15-17 people, one for each of the core subjects (English, mathematics, and science) and the Task Group on Assessment and Testing (TGAT), under the auspices of, and reporting directly to, the Department for Education. Members of the committees included teachers, education lecturers and academics, HMIs (Her Majesty's Inspectors of Schools), civil servants and representatives from industry. The committee membership and the chair were agreed, in other words, controlled, by the Department for Education, with some suggestions for membership being vetoed (Ball, 1990).

It was the view of the government, and particularly the Secretary of State, that the National Curriculum should be composed of discrete subjects, at least in part to reflect education in independent schools (Ball, 1990). His view was not shared by all those involved, some of whom, Ball reports, strongly believed that the curriculum should be considered as a whole. According to Ball (1990), the political atmosphere at the time was suspicious and critical of the educational establishment (discussed further in Chapter 4). The emphasis on subjects was at least in part to facilitate external testing, to allow judgements to be made about schools and teaching (Ball, 1990). The curriculum set out, in particular, what an average child should know in each subject at the age of 7, 11, 14 and 16, at what became known as the key stages. Knowledge was assessed in the key stage tests, known as SATs, at 7, 11 and 14, and in the GCSE examinations at 16. Fensham (2009) argues that this focus on testing has had considerable influence on the practice of science education, through the inevitable emphasis on those aspects of science which can be assessed through pencil and paper tasks.

The curricula, organised in terms of 'programmes of study', for the core subjects were written very quickly, each in less than a year. Ball (1990) reports that some committee members felt that in order to write one subject in the curriculum they needed to have a view of the whole; a view not shared by the Department for Education. Each subject group wrote the curriculum for the whole of compulsory schooling, from 5-16. The chair of the science group was a science educator, Jeff Thompson. The first chair of the mathematics group was also a scientist, the physicist Roger Blin-Stoyle, as originally was the chair of TGAT, Paul Black (Ball, 1990).

That the chair of the mathematics group was a scientist rather than a mathematician was, unsurprisingly, seen as evidence of the government's distrust of the mathematical establishment (Brown, 1996). The difficulties between the various factions of the mathematics group led to minimal progress being made, such that the first chair, Blin-Stoyle, resigned and was replaced with Duncan Graham, a former Chief Education Officer for Suffolk with a background in primary education who was neither a mathematician nor a scientist (Graham & Tytler, 1993).

Batteson and Ball argue that 'serious gaps exist in our knowledge of the ways in which contemporary education policy has been shaped and steered' (1995, p. 204) and consequently that diaries and memoirs, while often biased, can be useful sources of information as long as they are treated with 'critical scepticism' (*ibid.*). One such account is that of Duncan Graham (Graham & Tytler, 1993), the second chair of the mathematics working group. In his memoir, he suggests that:

> I am quite sure that the members of the mathematics working group did not realise precisely what it was that they were being asked to do. I certainly did not. (Graham & Tytler, 1993, p. 24)
>
> [It was] a task which nobody understood and the implications of which were enormous. (*ibid*., p.28)

These are astonishing admissions and perhaps reflect the speed at which the groups were being asked to work and the lack of an overall view of the curriculum.

2.2.2 Reforming the curriculum

The National Curriculum was produced in the timeframe required by the government and implemented from September 1989 without trialling. From the start there were issues with its structure and size (17 attainment targets in science), which proved unworkable. Less than 18 months after the first version was taught, Kenneth Clarke (then Secretary of State for Education) announced that a second version of the mathematics and science curricula would be prepared for implementation in September 1992 (Brown, 1996). A further version was introduced in 1995 and the curriculum has been reviewed and adapted multiple times since then (see Appendix 1). The revisions for mathematics and science, and for key stages within the subjects, have sometimes occurred at different times, further reducing the opportunities for coordination.

In 1993 the School Curriculum and Assessment Authority (SCAA) was created to oversee the curriculum and testing arrangements. This body was replaced in 1997 by the Qualifications and Curriculum Authority (QCA), later Qualifications and Curriculum Development Agency (QCDA). QCA/QCDA wrote and managed the curriculum until the agency was disbanded by the Coalition government in 2011. While QCA existed there was a semi-independent body responsible for the curriculum. Since 2011, writing the curriculum has come back under the auspices of the Department for Education. For the latest iteration of the National Curriculum there were separate writers for each subject and for each key stage within the subjects. Mathematics is embedded into the science content, with each section of the science curriculum containing a list of mathematics which should be included (DfE, 2015). There are not, however, any links or references to the mathematics curriculum itself.

In the late-2000s, the scientific learned societies (Royal Society, Royal Society of Chemistry, Society of Biology, Institute of Physics) and the Association for Science Education (ASE) came together as the Science Community Representing Education (SCORE). Concerns were formally raised by SCORE about the writing and review of the latest curriculum, suggesting that the process had been opaque, partly as the result of what they describe as unnecessary confidentiality. They suggest that the names of the authors, the civil servants and people in formal advisory groups were not released and that there was a complicated structure of groups who commented on the curriculum, with members of those groups not aware how they fitted into the picture. This opacity and complexity contrasted with the previous revisions overseen by QCA, which had included large meetings and consultations with interested parties from the science education community. The chair of SCORE, Professor Graham Hutchings, wrote to the Secretary of State for Education complaining that:

> The development process has been opaque and piecemeal. Over the last year versions of the Programmes of Study for the sciences have been drafted and critiqued by informal advisory groups, sub-groups and individuals. We understand that those involved have not always had a clear idea of where they fit in the process, how their contribution was being used or who else is involved. Additionally, appointed authors (who remain unknown to us) have been working with the civil servants to finalise these drafts. This level of complexity, coupled with unnecessary confidentiality, has caused concern within the science community. (Hutchings, 2012)

One result of the opacity is the obscuring of the influence behind the curriculum. The letter goes on to argue for the place of the SCORE member organisations (the learned societies and the ASE) in the development of the science National Curriculum:

> SCORE member organisations have an important role to play in this Review. Any Programme of Study for the sciences should have the support of these organisations prior to publication. (Hutchings, 2012)

An anonymous letter quoted in an editorial in the ASE in-house journal suggests that some teachers, who were invited to give advice, felt ignored:

> I had an active role in advising the Department for Education directly on the development of the new national science curriculum. I found the experience of working with civil servants to be incredibly frustrating because they largely ignored the strong advice given by subject experts. (Quoted in Hunt, 2014)

Functioning alongside the National Curriculum programmes of study are subject criteria which set out what must be included in an examined qualification with a particular title. Thus for 14-16 science there is both a programme of study and a set of subject criteria; at 16+ there are just subject criteria. These documents are used by the awarding organisations (historically known as 'exam boards' and then 'awarding bodies'), of which there are currently three in England (AQA, Edexcel and OCR), to write the specifications for their particular qualifications. The awarding organisations set the examinations and award the qualifications. They are in competition with each other and one, Edexcel, part of global education business Pearson, is a for-profit company. In planning their work, teachers generally refer to the awarding organisation specifications rather than the criteria or programme of study for students beyond the age of 14. The specifications and assessments are checked by the regulator, Ofqual (the Office of Qualifications and Examinations Regulation), to ensure that they conform to the criteria.

2.3 Mathematics within science

2.3.1 The school curriculum

In the first National Curriculum in England (DfES and the Welsh Office, 1989) no explicit links were made between the science and the mathematics curricula, although in the science curriculum there was a strong emphasis on communication, suggestive, at least, of links with English, which was lost in subsequent revisions. Orton and Roper argue that 'the possibilities of co-ordination were ignored in the creation of the National Curriculum, an innovation which might have co-ordinated the curriculum' (2000, p. 135).

By 2000, following several revisions, there was a very limited quantity of mathematics within the science curriculum. Orton and Roper, mathematics educators, went as far as to argue that 'science curricula within the 5-16 age range appear to be seeking to manage without mathematics, or at least to function on as little as possible' (2000, p. 146). Indeed, the NEAB examination board could claim that 'Candidates will not be prevented from demonstrating achievement in science by the use of […] mathematics which is excessively demanding' (quoted in Orton & Roper, 2000, p. 130). Orton and Roper suggested that the curriculum and the associated assessment system may not be aligned, with even less mathematics evident in examinations than in the curriculum itself:

> Science teachers, especially physics teachers, protest their problems in teaching the subject at this level, with its increased mathematical demands, even though examiners' reports appear to deny these problems. Is a different, perhaps less mathematical, version of the subject being examined than is being taught? (Orton & Roper, 2000, p. 146)

When there is very limited mathematics within science, science and mathematics departments in schools are even less likely to consider collaborating.

In their review of the key stage 3 curricula and the (now defunct) key stage 3 tests, Orton and Roper (2000), both mathematics educators, note that the data handling requirements in science were higher than those in the mathematics papers but that aside from this the mathematical demands were not high and fell well within the equivalent levels for mathematics.

Fairbrother (2008), a science educator, was more critical of the difference in the mathematical demands between mathematics and science.

> This mismatch represents an oversimplification of science, a failure properly to show what science at this level is about, a lack of opportunity for students to show what they can do and a failure to prepare students for the GCSE examination. It also fails to take advantage of using the same concepts and operations in science and mathematics to reinforce pupils' knowledge and understanding in both subjects. (Fairbrother, 2008, p. 112)

In the late 2000s, SCORE commissioned a series of studies about the content of science examinations. The reports indicated that 'the demand and type of the mathematics within the papers was limited' (SCORE, 2009, p. 3) and the full range of mathematics skills and techniques given within the specifications were not being assessed. The same problems were identified in A-level papers where, even in physics where the most mathematics was found, the authors demonstrated that the mathematics in examinations clustered around a few types of mathematics across all papers and was not a broad spread of all the potential mathematics according to Ofqual criteria (SCORE, 2012). As Orton and Roper (2000) had suspected, a different version of the A-levels was being examined than taught. So, the problem was not with the criteria for the A-levels, which included mathematics, but with the assessments not reflecting those criteria, and with Ofqual not challenging the mismatch.

There was far from universal agreement as to how problematic the small percentage of mathematical questions within science assessments actually was. Members of the scientific community were shown the data and the authors reported that, certainly for chemistry:

> Many felt that a chemistry examination should only be concerned with chemistry content and that the mathematics should be assessed in the context of chemistry. (SCORE, 2012, p. 50)

In other words, it is not enough that a science examination should contain mathematics; questions should be in the context of science and require scientific knowledge and understanding. The report also demonstrated a lack of alignment with mathematics courses such that some of the mathematics required for A-level sciences would not be covered in GCSE mathematics (SCORE, 2012).

How mathematics is dealt with in science has implications for the relationship between the subjects. Some science educators, such as Fairbrother (2008), argue that a lack of mathematics within science both oversimplifies science, and fails to take advantage of opportunities for reinforcing knowledge between the subjects. When science does not reinforce students' learning in mathematics, there is minimal incentive for either discipline to collaborate.

In 2010 there was a change of government and the new coalition government decided to re-write the National Curriculum and subject criteria for all subjects. In this latest iteration, the mathematics which could be included is embedded next to specific science topics in the GCSEs rather than just listed in an appendix (DfE, 2015). In the A-level criteria the subject content has not changed substantively but the mathematics appendix contains specific examples of how the mathematical skills can be used in science (Ofqual, 2011; DfE, 2014). The criteria for both GCSE and A-level also give the percentages of the marks which must be mathematical for each of the science subjects, as advised by the Smith report for Ofqual (Smith, 2013). For example, at A-level:

> The assessment of quantitative skills will include at least 10% level 2 or above mathematical skills for biology and psychology, 20% for chemistry and 40% for physics, these skills will be applied in the context of the relevant science A-level. All mathematical content must be assessed within the lifetime of the specification. (DfE, 2014, p. 24)

Not all the mathematical skills need to be assessed each year, which would make for a very long paper, but they do have to be covered 'within the lifetime of the specification,' although no one knows how long that will be.

The mathematical content of the GCSE science papers are now explicitly tied to the same tier in the mathematics GCSE:

> The mathematics should be at levels up to, but not beyond, the requirements specified in GCSE mathematics for the appropriate tier. (Department for Education, 2015)

This statement therefore apparently ties the tier of entry for students in mathematics to that in science. In other words, students taking higher tier science can be examined on mathematical content in the higher tier of GCSE mathematics, although students can be, and are, entered for different tiers in the different subjects.

Mathematical content in science O-levels was higher than that seen subsequently in GCSEs and some of the calls for an increase in mathematics in science examinations seem to be harking back to this previous era. For example, the Walport report to the government, which specifically recommended an increase in mathematics in science qualifications, found that:

> There was near universal agreement that the level of mathematics in science at GCSE and A-level has been significantly reduced. (Science and Learning Expert Group, 2010, p. 110)

However, science teaching in the 1980s was not without its problems. O-levels were designed to be sat by only about 25 percent of the school population and even then some of the mathematical requirements were deemed just too hard for this group. Some science educators including Shayer and Adey (1981) argued using a Piagetian analysis that the cognitive demands of O-level science were too high and that the mathematics which was focused on was often not the most appropriate. Even in the National Curriculum era, Dodd and Bone (1995) found that much of the mathematical content of key stage 3 science was simply too hard for students. The converse view is that removing mathematics from the curriculum misrepresents science (Orton & Roper, 2000; Fairbrother, 2008; Osborne, 2011); the level of mathematics which 'should' be present in the science curriculum is seemingly always going to be a matter of contention. The amount of mathematics within science will be very likely to impact the relationship between the disciplines, both in school and in policy development.

2.3.2 Undergraduate level

Alongside and feeding into wider unease about the mathematical content of science examinations were concerns about the difficulties which science undergraduates were reported as experiencing with the mathematical content of their courses. The Walport report specifically links such difficulties to the reduction in mathematical content in science examinations:

> The level of mathematics in science at GCSE and A-level has been significantly reduced, meaning that there is now a very notable jump to HE [Higher Education]. (Science and Learning Expert Group, 2010, p. 110)

Specific reported examples where students have difficulties include the irrational number 'e' at the base of natural logs (ln) being a 'mystery', leading to a failure to understand the fundamentals of chemical kinetics (Hoban, Finlayson, & Nolan, 2013) and a lack of understanding of logarithmic scales leading to students having no understanding of the pH scale (pH = $-\log_{10}[H^+]$) (Watters & Watters, 2006), which can cause problems in both chemistry and biology. There are also more general problems such as low mathematical confidence, particularly among bioscience undergraduates, a fear of mathematics and an expectation that bioscience courses will be largely descriptive, such that students do not anticipate having to do mathematics. Put together these often mean that students will not even attempt quantitative problems (Koenig, 2011). While there are concerns about students' use of mathematics in physics and their preparedness for undergraduate study in physics and engineering, mathematics A-level is a pre-requisite for entry onto such degrees. Even so, the high amount of mathematics required in university level courses still takes some students by surprise (Morgan, 2011).

England is unusual in comparison with other OECD nations in the low proportion of students who continue to study mathematics beyond the age of 16 (Hodgen, Pepper, & Ruddock, 2010). For many bioscience and even some chemistry degrees the minimal mathematical entry requirement is a grade C at GCSE (Koenig, 2011; Shallcross & Yates, 2014). It has been suggested in a number of reports that perhaps a post-16 qualification in mathematics should be an entry requirement, or at least an acknowledged preference, to give students a more accurate impression of what they will be expected to study in their degree course (ACME, 2012). However, there is an acknowledgement that such a requirement may put some students off (ACME, 2012). As only around 40 percent of those taking A-level biology currently take A-level mathematics (Koenig, 2011), this move would potentially leave a much smaller pool from which to choose applicants.

Students who have gained a B or C at GCSE may not have acquired a full understanding of several concepts which might be used in a science degree. For example: negative and fractional powers; scientific notation; solution of linear simultaneous equations; reverse percentage calculations; plotting graphs of exponential functions; working with quantities which vary in direct or indirect proportion; trigonometry; cumulative frequency diagrams and histograms; or probability calculations (Lee, Browne, Dudzic, & Stripp, 2010). This means that many students may not be able to manipulate numbers commonly used in science such as measurements made in microscopy in micrometres or concentrations in nanograms per litre. They are unlikely to recognise an equation for a straight line or be able to rearrange it. Rearranging other equations may also be difficult. If they start to study statistics at university they may not understand probability (Koenig, 2011). There is a mismatch between the expectations of academics and the mathematics students will have covered at school and are competent with. For example, academic staff expect students to understand logarithms and logarithmic scales (*ibid*.), but they are not covered in GCSE mathematics.

> One might argue that logarithms must be covered within A-level chemistry through understanding pH or in A-level biology through understanding exponential growth. However, the effectiveness of teaching of this sort of maths within A-level biology and chemistry is largely unclear. Anecdotal reports from students are that calculating pH, for example, is just taught through which button to press on a calculator rather than as a fundamental mathematical concept. (Koenig, 2011, p. 4)

> ‘I don’t know what log actually is, I only know where the button is on my calculator.’ (Student quoted in Watters & Watters, 2006, p. 280)

Part of the reason for the concern about students’ use of mathematics is that it has been found by a number of researchers that students’ prior mathematical understanding and achievements are one of the best predictors of success on undergraduate science courses. For example, Leopold and Edgar (2008) have shown that mathematical performance is positively correlated with success in undergraduate chemistry, while Loehr, Almarode, Tai, and Sadler (2012) found a strong positive association between mathematical experience and success on biological science courses. Although it should be acknowledged that both of these studies were conducted in the United States, they have been cited by the UK Higher Education Academy when reporting on UK undergraduates’ use of mathematics in science.

It has been proposed by a number of authors that the problem may not be that students do not have the knowledge of mathematics but that they have difficulties in applying it in scientific contexts. Grove and Pugh (2015) found that while students who had A-level mathematics could carry out formulaic or procedural mathematical problems, they struggled to take a chemistry problem and successfully apply appropriate mathematics in order to solve it, and suggest that similar issues were found in physics.

At least two responses to the difficulties undergraduate students have using mathematics in science have been suggested. One is that students are taught the mathematics they need once they are at university, where it has been found that teaching mathematics in the context of biosciences (Koenig, 2011) or chemistry (Grove & Pugh, 2015) increases motivation. Indeed Grove and Pugh (2015) found evidence that in some chemistry departments results do not follow the often-described correlation of more incoming mathematics leading to higher grades. Yates (2014) acknowledges that it can be difficult for academics, who are confident 'playing with a mass of differential equations,' to understand the mathematical anxiety suffered by many students.

The second response to undergraduates' difficulties with science is to suggest that the difficulties should be solved in schools before students arrive at university. The argument that the so-called 'maths problem' should be solved by schools has its roots in suggestions that undergraduates are unable to use mathematics within science due to the teaching they receive in both science and mathematics. For example: 'Mathematics learning at school can be very procedural, learning for the exam rather than for a deep understanding' (Koenig, 2011, p. 4). The universities, through the Higher Education Academy, are some of those who are arguing for inclusion of additional mathematics into A-level sciences (for example Koenig, 2011, and Hodgen, McAlinden and Tomei, 2014).

While there are concerns from within SCORE and elsewhere about the perceived reduction in mathematical demand in both GCSE and A-level sciences, Clesham (2013) found that there was a low incidence of calculation questions in school science examination questions internationally as well as in the UK. The regulator, Ofqual, in a report into A-level chemistry, even asked if there was too much mathematics in chemistry A-levels as the mathematics requirement was higher than in other similar examinations internationally, although it noted that most other jurisdictions required the separate study of mathematics (Ofqual, 2012). It is interesting that internationally even where students are required to continue with mathematics, they are apparently not required to use that mathematics in the context of science, or at least chemistry.

There are thus identified concerns with students' use of mathematics within science, particularly at undergraduate level. How these difficulties could or should be addressed is a matter of some contention. Should it be within universities themselves or within schools, for example by increasing the amount of mathematics within science? The Walport report recommended an increase in mathematical content of science qualifications, but acknowledged that this could be challenging for some students:

> We acknowledge that some students can find mathematics daunting, but if the material is taught and assessed well, demanding mathematics content can be made accessible to a wider audience and rather than providing a blockage, should enhance science learning and motivate learners through a deeper grasp of the subject. (Science and Learning Expert Group, 2010, p. 110)

That demanding mathematics content 'should' enhance science learning is perhaps a recognition that there is very limited research to support such a supposition. The terms of reference for the Science and Learning Expert Group, headed by Walport, are that they are to 'focus in particular on […] stretch and challenge of the most able learners' (Science and Learning Expert Group, 2010, p. 76), and yet these recommendations have implications for all learners of science. I will explore the research about mathematics within science in Chapter 3 and return in Chapters 8-10 to the focus in science education on the 'most able'.

2.4 Science within mathematics

Orton and Roper (2000) reported that UK mathematics textbooks for 11-year-olds contained minimal science, with those for 14-year-olds containing some, but confined to specific areas of the curriculum, particularly interpretation of travel graphs and standard form. They argue that:

> Throughout the National Curriculum the emphasis is upon the application of mathematics to the 'real world' and the siting of mathematics within a context, however unlikely that context might be. Yet the interpretation of the phrase, 'real world', and the contexts used include very few which might be called science-based. (Orton & Roper, 2000, p. 132)

This lack of science may be due in part to mathematicians decrying what they see as extraneous text in mathematical textbooks as they perceive it as making it more difficult for students to see and understand the mathematics (Shanahan & Shanahan, 2008).

Orton and Roper argue that the mathematics required for science at both key stage 3 and 4 is undeniably present within the mathematics National Curriculum. It may be reasonable to ask if science should expect more from mathematics than they currently receive, but:

> [T]he picture which emerges at a policy level from England and Wales is that, if mathematics wishes to serve itself and all its many interested parties, the obligation to science is simply one of many competing demands and relatively unimportant in the larger scheme of things. (Orton & Roper, 2000, p. 133)

In addition to a lack of interest at policy level, there may also be a lack of interest at a personal level: 'the view that mathematics is a subject to be studied in its own right, that it owes no allegiance to the sciences is […] not uncommon today' (Orton & Roper, 2000, p. 131).

In the 2013 key stage 3 curriculum for mathematics there is an acknowledgement that mathematics is important for science and that students should be able to use their mathematical knowledge in other contexts:

> Mathematics is […] critical to science, technology and engineering. [Pupils] should also apply their mathematical knowledge in science. (Department for Education, 2013e, p. 2)

It is not clear if it is the responsibility of mathematics or science teachers to ensure that pupils apply their mathematical knowledge in science.

2.6 National STEM policies

The national STEM policies were an unusual example of recent policy making in that they involved collaboration between the mathematics and science education communities. STEM usually refers to Science, Technology, Engineering and Mathematics, but to some it is Science, Technology, Engineering and Medicine and for many outside the 'STEM community' it means nothing (Breiner, Harness, Johnson, & Koehler, 2012). The reasons for the inclusion of these four disciplines is unclear and even the UK National STEM Director, John Holman, has admitted not understanding the logic behind it: 'Whatever may have led us to cluster these subjects together, it cannot be their similarities, because they have few' (Holman, 2011, p. 6).

Calls for a greater focus on science and mathematics education often arise from concerns about science more broadly (Wong, Dillon, & King, 2016). In England, ascribing what happens in schools to perceived problems facing science dates back at least as far as Charles Babbage in his 1830 treatise, *Reflections on the decline of science in England and on some of its causes*:

> The tastes and pursuits of our manhood will bear on them the traces of the earlier impressions of our education. It is therefore not unreasonable to suppose that some portion of the neglect of science in England, may be attributed to the system of education we pursue. (Babbage, 1830)

Over 170 years later the same idea – that neglect of science can be traced to issues with education – recurred in a UK government-commissioned review conducted by Sir Gareth Roberts (2002). The government were concerned that the supply of high quality scientists and engineers should not be a constraint on future research and development (R&D) and innovation performance, due to the high importance such activity had for the economy. At the heart of Roberts' review, therefore, was a fear that the country would become less economically competitive unless changes were made. The actions advised include many directly related to mathematics and science education. Jenkins argues that viewing economic competitiveness as directly linked to science education has consequences in directing the objectives of the curriculum 'towards the production of an adequate number of well-qualified scientific personnel' (Jenkins, 2009, p. 81).

A High Level STEM Strategy Group was formed which included government ministers, civil servants and representatives from each of the lead organisations, together with other organisations such as charitable trusts, subject associations and learned societies. This group also brought together the previously separate DfE Maths Programme Board and School Science Board. Mathematics and science did not play an equal role in the creation and dissemination of STEM policies. The side-lining of mathematics was shown by the appointment of a science educator to the role of National STEM Director. This prioritising of science appears to have continued through the formal STEM programme as the later STEM Evaluation noted that there was:

> A continuing lack of understanding and appreciation amongst those working in STEM education of the role of maths in STEM. (NFER, 2011, p. 95)

In spite of all the activity at government level, the idea of STEM never found real traction in schools. NFER (2011) found understanding of the term STEM was varied at school level and noted a lack of understanding of STEM as a construct.

2.7 Summary

Fensham (2009) argued that it is important to understand the political and cultural context of science education policy. I have shown in this chapter that policy can have a direct impact on the practice of science education in schools. For example, national policy led directly to a change in the patterns of participation in science for 14-16 year olds, with the National Curriculum and GCSEs leading to all students studying science to the age of 16. Less positively, it also led to science education focusing on that which can be assessed through pencil and paper tests. I have shown that those writing the original National Curriculum lacked an overview of the whole curriculum, although some would have preferred to work in a less trammelled way. More recently, the latest National Curriculum development was described as opaque and unnecessarily confidential by the scientific societies as they argued for a greater role in producing the science curriculum.

I have demonstrated that the amount of mathematics within science is contentious and there is a lack of agreement about which mathematics should be focused on and how much should be present. Calls for more mathematics within science education have come in recent years from universities, some of which struggle to deal with the difficulties that science undergraduates can have with mathematics. The view that economic competitiveness is directly linked to science and mathematics education has also led to calls for changes in the science curriculum, and a greater focus on producing people qualified in science and mathematics.

This political and cultural context forms the backdrop to this study. In the next chapter I review the small number of existing studies of mathematics-science collaboration.

Chapter 3
The relationship between school mathematics and science in the literature

In Chapter 1, I demonstrated that a number of authors have drawn attention to the paucity of research into the relationship between school science and mathematics education. In this chapter I review the existing research, asking in particular what research has been carried out into the relationship at school level, and what has been reported about the benefits and difficulties when mathematics and science departments work together.

3.1 Searching the literature

Although there are some reviews of the literature (discussed below), on the whole searching is difficult as there are differences in language. A number of literature searches were attempted using ProQuest and other databases, websites including Google Scholar, and other sources. Systematically searching for literature about the relationship between science and mathematics education was not straightforward. As explained in Chapter 1 there are very few empirical studies, but even among those which do exist there are inconsistencies with terminology. For example, many authors call any attempt at the two disciplines working together 'integration' but a number of authors (for example: Czerniak, Weber, Sanmann & Ahern, 1999; Berlin & Lee, 2005; and Williams *et al*., 2016) note issues with the term integration and the lack of an agreed definition as to its meaning.

Berlin and White (2012) note a plethora of terms in the literature which are used to refer to what they would describe as integration: integration; connection; co-operation; co-ordination; correlated; cross-disciplinary; fused; interactions; interdependent; interdisciplinary; interrelated; linked; multidisciplinary; trans-disciplinary; unified. In the UK the term cross-curricular is also used. For some authors integration means the traditional discipline boundaries are blurred or even lost, while for others integration retains boundaries but stresses the interactions between disciplines (Lederman & Niess, 1998). The lack of clarity means that while 'integration' might suggest mathematics and science are taught in the same classroom by the same teacher at the same time, a variety of other meanings are evident in the literature, with authors not always articulating exactly what they mean by any of the terms above. The lack of agreed definitions makes searching the literature for relevant sources particularly frustrating. Due to the lack of agreed definitions and consequent imprecision of terms used, it is difficult to put boundaries around studies of interest and to say with any degree of certainty how many relevant studies have already been carried out. I have found that the most effective and efficient way of searching for literature is to use the references from these reviews, together with those which cite them. Many of the existing reviews focus on the integration of mathematics and science, although some of the more recent ones have a broader focus on STEM.

To make searching more challenging, not all the science sources refer to 'mathematics', with some instead using the terms 'numeracy' or 'quantitative skills'. The use of neither of these terms is well-delineated. For example, numeracy can be defined as a quality of successful learners of mathematics or a 'proficiency which involves confidence and competence with numbers and measures' (ACME, 2011, p. 5). The Advisory Committee on Mathematics Education (2011) argue therefore that numeracy is not a definable subset of mathematics. Following their lead, I have chosen to use the term mathematics throughout to include both what might be termed numeracy, and also statistics. Although I have tried to avoid 'numeracy' where at all possible, it is used by other authors.

3.2 Analysis of the literature reviews

I begin the survey of the literature by summarising the existing reviews. These reviews are not necessarily attempts to review the whole field, probably due to many of the same difficulties described above.

3.2.1 Czerniak *et al.*: the dearth of studies

In a US-based review of integration literature, Czerniak, Weber, Sanmann & Ahern (1999) noted both the dearth of empirical studies and difficulties with terminology. They listed some advantages and disadvantages of integration and some obstacles needing to be overcome to allow integrated teaching, including teacher preparation, the structure of the school day and the state-defined curricula. They suggest that further research is critical in evaluating whether the many claimed benefits to integrated teaching are actually found in practice and understandably contend that integrated teaching can only be justified if students' understanding of the content is enhanced.

3.2.2 Orton and Roper: A troubled relationship

Orton and Roper (2000) argue that there is room for improvement in communication between the disciplines in their review *Science and Mathematics: a relationship in need of counselling?* Their focus is the situation in the UK, particularly England, and takes concerns raised about undergraduates' difficulties using mathematics in science as the starting point. In reviewing 20 years of literature, Orton and Roper note that the 'science-mathematics issues considered relevant by teachers differ according to whether one is a scientist or a mathematician' (p. 133) and between primary, secondary and higher education. They demonstrate that traditionally the concern tended to be whether the mathematics needed in science had been taught in mathematics by the time it was required in science. What they call a 'de-mathematising' of science (i.e., a reduction in the mathematical content of science) had lessened these difficulties, but replaced them with a broader unease as to whether students were being given an accurate impression of science if it lacked mathematics. From the mathematics education literature Orton and Roper extract three reasons why students do not find it straightforward to apply what they have learnt in mathematics to other areas of the curriculum: mismatch of the syllabus, where students have not covered the mathematics required by the time they use it elsewhere; the attitude of science teachers in giving the impression that supporting mathematics does not need to be understood as long as it can be applied; and the attitude of mathematics teachers who show no interest in how mathematics is used in other subjects.

Orton and Roper suggest that there have always been opportunities for conflict between science and mathematics and, like Osborne (2011, 2014), they find that little has been done to forge links and to develop common approaches. They report a number of suggestions that have been made to improve the relationship between the subjects: liaison, suggested by a number of authors; encouragement, with no negative messages about numeracy; science teachers developing knowledge of the mathematics curriculum; teachers finding out about what students do and do not know and understand; helping students in the context of science to remember, practise, understand and make decisions relating to the use of mathematics; interdisciplinary policy documents; the study and elimination of inconsistencies; agreement over terminology; a reduction in mathematical manipulation in physics together with an emphasis on mathematical manipulation at all levels in mathematics; reinforcement of mathematical skills in physics (or science more broadly); and the use of examples from science in mathematics.

They conclude that 'the connections between the two areas appear to be weakening so far as the education enterprise in schools is concerned' (p. 145) and 'science and mathematics at school level are not as interdependent as history and philosophy might suggest they should be' (p. 146). They end with a call for further research, particularly focusing on students' understanding of the links between scientific situations and their mathematical expressions with the hope that it will lead to a better appreciation of mathematics within science:

> Greater understanding of this complex interrelationship may well assist teachers and students at all levels to better appreciate the application and use of the mathematics within scientific practice, and thereby to feel more comfortable with a concept of science as a subject that is mathematically orientated. (2000, p. 147)

3.2.3 Pang and Good: Science focus

Pang and Good (2000) survey the literature on 'integration' from the 1990s, using the term to mean any research about connecting mathematics and science. They found an on-going trend in research was science-focussed integration with science topics to which mathematics had been added being far more prevalent than mathematical topics with added science. They are concerned that relatively few researchers have discussed substantive psychological or philosophical reasons why integrating science and mathematics would improve students' understanding. Nevertheless, they conclude that further emphasis on integration is desirable 'in order to help all students become more scientifically and mathematically literate' (p. 78). This is arguably quite a large claim from a relatively small body of research (14 studies, 4 of which were in the context of pre-service teacher education) and perhaps demonstrates the strong beliefs that some authors have about integration, even where there is minimal empirical data to back up their claims.

3.2.4 Venville *et al.*: Factors affecting integration

Venville, Wallace, Rennie and Malone (2002) from Australia argue that reasons to integrate include enhancing pupil engagement with school and improving pupils' ability to transfer their learning to be able to use it when and where it is needed. They draw on the work of Bernstein to help explain the existence of boundaries between disciplines and why they are difficult to cross. They suggest some of the factors affecting integration include: teacher recruitment and identity; subject histories; assessment structures; department politics; subject status; pupil futures; an overcrowded and content-laden curriculum; traditional patterns of assessment; parental pressure for traditional academic standards and subject-based qualifications; instructional periods; textbooks; curriculum guides; staff who were trained in their disciplines and have developed long-standing attachments to them; a lack of a culture of school collaboration; teacher concerns that integrated teaching might lead to students thinking of subjects as an 'amorphous mass'; and tensions with ability grouping.

Venville *et al.* found a variety of integrated practice in school settings. They resisted placing the different versions of integration along a curriculum continuum, not wishing to imply 'that more integration was synonymous with better integration' (p. 76). I have followed their lead, and have likewise not drawn up a continuum of the collaborative practice which I found in schools.

They acknowledge that assessing learning following integrated teaching may be difficult:

> For those who value the traditional, discipline-based subjects, the learning must be evaluated in terms of understanding the important concepts in the subject. But for those educators who value integrated curriculum, the outcomes are not so well defined. (p. 61)

As a result, they argue that integrated curricula do not fit well with the expectation in many countries that the school curriculum should be academically orientated towards traditional disciplines, and should emphasise written work, individual study and examinable aspects of the syllabus. In an era when clearly defined outcomes against arguably narrow subject criteria are the most highly prized in education, it is perhaps easy to see why, if integrated teaching has fuzzier aims, it struggles to gain much traction. Given how strongly established the disciplines are in schools, they propose that integrated approaches should not attempt to ignore the traditional subjects.

Venville *et al.* suggest that the research on learning in integrated contexts is fragmented and lacks theoretical continuity. While acknowledging the practical difficulties that integration presents, they nonetheless continue to promote integrated teaching, arguing that it is more relevant, more interesting and aligned more closely with the way that pupils learn.

3.2.5 Berlin and Lee: A lack of theory

Berlin and Lee (2005) conducted a US-focused survey of the number and nature of documents relating to science and mathematics integration from 1901-2001. As with other authors, they discuss issues with terminology which they suggest makes it difficult to compare across different studies. They demonstrate and welcome a trend towards a greater focus on secondary (compared to middle school) education where they perceive integration is harder. They note that there had been a rise in work proposing theoretical models of integration but argue that more empirical research grounded in those theoretical models is required.

3.2.6 Becker and Park: Meta-analysis

Becker and Park (2011) undertook a meta-analysis of 28 studies into the impact of integration in STEM subjects by calculating 33 effect sizes. They used the Education Resources Information Centre (ERIC) and found 98 studies; only 28 of these included sufficient empirical data to be included in the calculations. They too note that inconsistency in terminology makes searching databases more difficult. They conclude that their work can only be a preliminary meta-analysis as there are so few empirical studies on the effect of integrative approaches on student learning. Among their conclusions were that integrative approaches appeared to have a greater effect size for younger students. This finding is possibly because in elementary or primary school the teachers have more flexibility in their curriculum and are more likely to teach multiple subjects. They suggest that collaboration among STEM teachers is one of the challenges to integration at secondary level.

Perhaps Becker and Park's most noteworthy finding is that when science is integrated into technology and engineering the effect sizes were relatively large for all subjects, but when mathematics was integrated the effect sizes were much smaller, particularly for mathematics itself where some of the effect sizes were negative. They call for further research to understand why, of all the STEM subjects, mathematics benefits the least from an integrated approach. Although Becker and Park do not suggest reasons for mathematics' smaller effect sizes, it may be related to Pang and Good's (2000) finding that mathematics concepts are rarely regarded as being of primary importance in integration, with the focus tending to be on science learning. Becker and Park's finding may also relate to Bennett, Braund, & Sharpe (2014) who report that while students appreciate contextualised learning activities in science (which could include science integrated with engineering or technology), they have negative attitudes to contextualised learning activities in mathematics, where the context is often perceived as irrelevant.

Becker and Park do, however, suggest that mathematics may benefit from integrative approaches in spite of the effect sizes through increased student interest, although Bennett *et al*.'s (2014) finding would appear to contradict that view. One could question the value of increased student interest if it is not leading to an increase in mathematical understanding, although Becker and Park suggest that understanding may perhaps develop over the longer term following the rise in interest. This paper again shows researchers retaining a belief in the educational value of integrative approaches in spite of evidence to the contrary.

3.2.7 Honey, Pearson and Schweingruber: Integrated STEM education

Honey, Pearson and Schweingruber (2014), in a US report on 'integrated STEM education', admitted that the committee producing the report was unable to define this term. They nevertheless give five goals for STEM education from the literature: STEM literacy; twenty-first century competencies; STEM workforce readiness; interest and engagement; and ability to transfer understanding across STEM disciplines.

STEM literacy is a relatively new idea which the authors recognise is not well defined in the literature or in practice, although there is a body of literature on aspects of literacy in the individual disciplines, most of it contested. According to the authors, twenty-first century competencies are:

> A blend of cognitive, interpersonal, and intrapersonal characteristics that may support deeper learning and knowledge transfer. Cognitive competencies include critical thinking and innovation; interpersonal attributes include communication, collaboration, and responsibility; and intrapersonal traits include flexibility, initiative, and metacognition. (p. 35)

The authors give a broad definition of STEM workforce readiness, including increasing the number of people choosing to follow STEM degrees and careers. They relate career choice to the goal of increasing interest and engagement. They found that some research stresses increased engagement among all students, some is more specifically focused, for example on traditionally under-represented groups.

The ability to make connections among STEM disciplines, Honey *et al*. found, was defined in a number of ways including 'recognizing and applying concepts that have different meanings or applications across disciplinary contexts (i.e., transfer)' (2014, p. 37). Transfer was also noted as one aspect of twenty-first century competencies and appears in this report to be a highly prized goal of integrated education. In their review of integrated STEM education programmes Honey *et al*. found 'surprisingly few in which the goal of making connections was stated explicitly' (p. 37), although they suggested that it was an implicit goal in many.

Honey *et al*. admit that many of the goals would be difficult or impractical to measure. As a consequence, therefore, it would be virtually impossible to show that integrated education leads to improvements in these desired outcomes compared to the more traditional discipline-based education. They also suggest reasons why integrated instruction may actually impede learning. It could place 'excessive demands on resource-limited cognitive processes such as attention and working memory' (2014, p. 78). In other words, learners struggle to process multiple pieces of information simultaneously and doing so is very cognitively demanding. Integrated instruction attempts to build bridges between ideas which are not well learned or understood. It could obscure 'important differences in STEM disciplines about how knowledge is constructed and revised' (p. 78). Perhaps as a result, they suggest that one emerging view is that for students who have mastered knowledge in the original disciplines an integrated approach will lead to greater learning gains than for those who struggle in one or both of the original domains.

Honey *et al*. argue that making connections is difficult for students, even in integrated teaching, and needs to be made explicit, otherwise the additional complexity required to make connections could even inhibit learning:

> Without effective guidance, the effort to make connections among multiple disciplines in the context of a complex problem or situation could overwhelm students and inhibit learning. (2014, p. 84)

And,

> STEM connections that may appear obvious to teachers, curriculum developers, and disciplinary experts often are not obvious to novice learners and cannot be assumed to occur simply because certain concepts and practices are introduced at the same time or place. Integrated STEM instruction needs to make connections explicit to students. (2014, p. 98)

Their arguments thus challenge the assumptions of some authors that integrated teaching is necessarily desirable, even in the face of evidence to the contrary.

3.2.8 Williams *et al.*: Obstacles

In a review of interdisciplinary mathematics education, albeit not focused specifically on science, Williams *et al.* note that:

> Inter-disciplinary work can be difficult, confronting certain sorts of obstacles, power structures, and questions of identity, differences in understandings of knowledge, discourse and practice. (2016, p. 6)

Given these obstacles, the surprise is perhaps not that inter-disciplinary work or integration is rarely found, but that it is found at all. Williams *et al*. argue that as a person becomes more associated with a discipline and identifies with it, they can become blind to other disciplines, or see other disciplines in a distorted way, creating further challenges to working in an interdisciplinary manner.

In particular, they identify a problem with interdisciplinary projects. In the normal organisation of society, products are exchanged by means of what they call a 'generalised exchange form' (p. 10); in most instances this takes the form of money. Participants in the exchange know what they are giving and what they are receiving. Williams *et al*. argue that when two or more disciplines work together they may have no medium of exchange. In other words, when science and mathematics, for example, come together, there is nothing obvious to exchange. They argue that in consequence there is difficulty in defining the common object – i.e., the project and project outcomes – which often leads to the failure of projects designed to be interdisciplinary. In successful projects the object (i.e., the project outcomes) makes sense within each of the disciplines. Thus considering the outcomes of a joint enterprise, and how those outcomes contribute to broader educational outcomes in each of the disciplines, is arguably key to successful interdisciplinary work.

3.2.9 Summary

From these reviews it is possible to see that there are many factors which affect or impede collaboration (or integration or interdisciplinary work), and overall it would appear that collaboration is both difficult practically and poorly described theoretically. Even so, many authors who have explored the practical difficulties continue to promote and to call for integrated teaching (for example Venville *et al.*, 2002, and Becker and Park, 2011). Reasons given for collaboration can be summarised into three main categories: that there is an overlap between the disciplines, such that collaboration is the logical response; the desire for improved transfer; and to meet an aim for an increase in student engagement. The calls for further research are likewise consistent across the reviews, with many authors calling for a better theoretical description of collaboration or integration and the challenges it presents.

3.3 Key themes

In this section, I will exemplify some key themes with specific instances, namely: graphs and graphing, often considered a topic or area of work where there is considerable overlap between mathematics and science; transfer between mathematics and science; fear and lack of confidence; work with pre-service teachers; teaching for transfer; students use of mathematics in science; and language differences between mathematics and science. Additionally, I include a summary of some of the papers in a special issue of the ASE journal *School science and mathematics*. The studies and position papers in this section have been chosen because of the specific contribution they bring to the discussion of the relationship between school science and mathematics. Some of these themes, such as transfer, were identified in the discussion of the review papers above but are discussed here in more detail. Some of the papers highlighted in this section are included in some of the reviews.

3.3.1 Graphs and graphing in mathematics and science[1]

In this section, I examine the nature of graphing in both subjects and discuss the differences between them. In particular, I use the example of graphing to explain why mathematics and science teachers may struggle to work symbiotically and why students may have difficulty in transferring learning from one discipline to the other.

Graphs are important in both mathematics and science and thus developing students' graphicacy or graphical literacy is a key goal in both subject areas. Graphs are used in both disciplines to convey information, to summarise results, or to display relationships. Given the comparable usage, it would seem that the teaching of graphs and graphing might be an area in which science and mathematics teachers could work together, as called for by Osborne (2011, 2014) and others as discussed in Chapter 1.

Osborne suggested that some science teachers operate with a vaccination model of mathematics (2014). In other words, some science teachers believe that students should learn mathematical skills, tools and thinking in mathematics lessons (the vaccination), and then be able to use that seamlessly within science. The use in one subject of what has been learnt in another is known as transfer (explored further in Chapter 4) and is considered problematic by science teachers, as Needham describes:

> Teachers have long been concerned about the difficulties their students experience when transferring what they learn in their mathematics lessons into the science classroom. (Needham, 2016, p. 14)

[1] This section has been published as part of Wong (2017). *Variation in graphing practices between mathematics and science: implications for science teaching.* School Science Review*, 98(365), 109-115.*

These difficulties reflect what was found by the AKSIS (ASE King's Science Investigations in Schools) project team:

> Many teachers we interviewed recognised the difficulties that pupils had with graphs, but few had made a point of teaching pupils about the construction and use of graphs. (Goldsworthy, Watson, & Wood-Robinson, 1999, p. 2)

3.3.1.1 Uses of graphing

By the time they finish primary school at age 11, most children can use graphs to make a pictorial record of numbers they have found in the world around them (Department for Education, 2013a, 2013b). To both mathematicians and scientists the real value of graphs, along with presenting information, is their predictive power and so it is the relational representation expressed in the graph which is most commonly the focus of teaching in secondary schooling.

In school mathematics a graph is often thought of as a representation of an exact or idealised relationship which is described by a mathematical equation (Booth, 1981). The nature of the mathematical relation to be graphed and the form of the graph are stressed. In consequence, there is little treatment of errors or discussion of departures from the exact relationship. It is emphasised that points which do not lie on the line do not fit the relationship in question. Little attention is usually paid to what the variables actually represent.

In contrast, in science the nature of the variables is far more important and values to be plotted are often derived experimentally. The, often unstated, objective is to see which mathematical model best fits the data (Booth, 1981) and a *line of best fit* may be drawn, which may or may not pass through any of the plotted points. The difference from what is expected in mathematics is quite distinct: in mathematics a point not on the line is one that does not fit the exact relationship; in science it can be part of natural variation in the data collected or an anomalous result. There is, consequently, no treatment of experimental error in mathematics while it is a key part of science. For example, in a graph of mass added to a spring against extension of the spring, the assumption is that the points *should* all lie on the line. That they do not is due to experimental error, and explaining where these errors come from and their effect on the data is part of learning to evaluate methods and explain uncertainty – key ideas in the 'working scientifically' part of the science curriculum (DfE, 2015).

In other words, students may be asked to draw a graph of a function in a mathematics lesson and in a science lesson to draw a graph of their results. Booth (1981) notes that the difference between these two activities can mean that while students may well be able to do both proficiently they may not understand the relationships and important differences between the two tasks. Therefore students who do not appreciate the difference between what a graph represents in mathematics and in science may assume that the points which are not on the line are simply wrong.

3.3.1.2 Graphing activities

The different uses of graphing in mathematics and science lead to differences in the types of tasks and activities which are prioritised and taught. In a comprehensive and widely cited review of research from both mathematics and science perspectives into graph education, Leinhardt, Zaslavsky and Stein (1990) break down what students have to do into two types of actions: interpretation (for example reading or gaining meaning from a graph) and construction (for example plotting a graph, determining an equation from a graph), although these are not mutually exclusive categories. Both these actions can be either quantitative or qualitative. They explain that:

> Construction is quite different from interpretation. Whereas interpretation relies on and requires reaction to a given piece of data (e.g. a graph, an equation, or a data set), construction requires generating new parts that are not given. (1990, p. 12)

In mathematics, interpretation might be looking at a given graph and determining where its x or y intercept is, or calculating the gradient. Construction might involve sketching graphs of equations for a variety of functions. In the statistics section of the mathematics curriculum, students might work with ‘real’ numbers and be expected to group data and draw graphs such as cumulative frequency curves.

In science, a graph might reflect a particular situation or phenomenon. If so, interpretation might well involve shifting from the graphical representation to the situation or phenomenon itself. This is a less commonly required skill in mathematics education. For example, to interpret a graph of enzyme action may also require understanding the effect of temperature, such that an increase in temperature may not lead to a consistent increase in reaction rate. Both an understanding of the graph *and* an understanding of the scientific situation are required to make sense of the data.

Of construction tasks, two are particularly relevant to science education: prediction and scaling. Prediction involves conjecturing from part of a graph where other points which are not given should be located. Leinhardt *et al.* (1990) argue that at the heart of most prediction tasks is an act of construction – which can be done either physically, by drawing on the graph, or mentally. Furthermore, they note that not all prediction tasks require the same skills. Some are more reliant on estimation and perhaps measurement skills, whereas others depend on pattern recognition. Crucially for science, being able to predict also requires that the student can interpret or understand the situation, behaviour or phenomenon under investigation, and also understand what the representational graph should look like.

Scaling tasks are those where the focus is on axes, their scales and units. In virtually all graphs in science the units are important because the graphs are representations of real life situations. The units, and consequently the scales, are also often different on each axis and thus learning how to choose and construct a sensible scale is a key part of learning to graph in science. When scales are changed the resulting graph can look very different which can cause confusion for students. As noted already, for the majority of the graphs drawn in mathematics there is little attention paid to what the variables actually represent and thus there is limited focus on units. This leads to less attention being paid to learning how to choose and construct sensible scales.

3.3.1.3 The role of context

Another difference between the use of graphs in mathematics and science that Leinhardt *et al*. (1990) see is that of the role of the situation or context. They suggest that mathematics educators will sometimes use real-world contexts for learning about graphs and although these may be taken from science, the point is the mathematics. Mathematical ideas may be better understood in a context that students can relate to, but the aim is for better understanding of the mathematics or mathematical function rather than the context itself.

Leinhardt *et al*. (1990) suggest that there is insufficient evidence to argue that the 'real-world' contexts in mathematics necessarily support the learning process. This is a very different situation, perhaps even the reverse, of the use of context within science. Graphs are seen as an aid to understanding the phenomena being investigated through being representations of observations and aiding the detection of underlying patterns. Knowledge of the context is essential in interpretation.

3.3.1.4 Words and terms

Across mathematics and science similar processes are called by different terms, and entities which are quite distinct are given the same name. There are at least three names given to graphs in mathematics which could cause confusion for students graphing in science.

The first is scatter graphs. These are in the statistics section of the mathematics GCSE, where students are expected to be able to draw graphs of bivariate data (that of two variables) and to draw a line of best fit if appropriate (DfE, 2013d). The second are line graphs. These are used for numerical data when there is a need to show a trend such as changes over time. In this type of graph in mathematics each of the points on the graph is joined by a straight line, dot-to-dot style. The third type are 'vertical line charts' or 'vertical line graphs' and are used for the type of data which would more commonly be shown on a bar chart in science.

In contrast, in science bivariate data can be graphed using either scatter or line graphs. Scatter graphs are used for data where there is underlying variability in the things being measured, as often happens in biological systems. A line graph in science is used for data from relationships between two continuous variables. These are found across the sciences but particularly in physics. They are constructed by plotting points and often then drawing a line of best fit. The 'vertical line graph' from mathematics does not tend to feature in science, and if it did would be called a bar graph.

Boohan (2016) has argued that even the different sciences have different ways of handling data leading to different graphing practices. However, he demonstrates that this is not due to disciplinary peculiarities but to the different types of data that each science is concerned with, as different types of data need to be handled in different ways. Boohan (2016) notes that there are many different types of graphs and charts which students might be expected to draw in science. Which would be the most appropriate to use depends on the nature of the data to be represented. While students may be competent at constructing graphs they may, however, be unable to distinguish which type would be most appropriate to use in a particular case.

Even seemingly simple decisions about when and how to draw a line in the data are not as straightforward as they first appear, as many authors have argued (including Booth, 1981, Leinhardt *et al*., 1990, Goldsworthy *et al*., 1999, and Boohan, 2016). In mathematics, a line, and thus a line of best fit, is by definition straight. In science both 'straight lines' and 'curved lines' are used and graphs which contain a curved pattern are called line graphs. Whether joining the points is appropriate depends on the data in question, but understanding this aspect is challenging for students. The distinctions can be subtle and it is difficult to write any hard and fast rules. The decision largely depends on understanding what information the expected line can be expected to provide and this is not a trivial matter.

In consequence, students often do not know when and how to draw a line and this decision is complicated by the seeming contradictions between what they learn in mathematics and in science. For example, when students are asked to draw a line of best fit in science they may produce a straight line even when a curve is more appropriate if they have been taught in mathematics that a line is straight (and must be drawn with a ruler). In a line graph in mathematics, different data points are joined by straight-line segments (dot-to-dot) but usually in science they are not and a line of best fit is drawn which might not pass through all the points (Boohan, 2016). This can be frustrating for the science teacher who does not understand why students would join the dots in this way. Students must learn that using the conventions of one discipline in the other is not correct and may well struggle both to do so and to appreciate why the differences are necessary.

3.3.2 Differences in epistemology

Lederman and Niess (1998) argue that in mathematics and science there are different epistemologies, in other words different ways of knowing and building knowledge. They suggest that while it is helpful to stress the connections between the two subjects, the nature of science and mathematics are fundamentally different. Lederman and Niess demonstrate how the nature of mathematics shares many features with the nature of science, but the use and importance of empirical evidence and data is a key area in which the domains appear to diverge.

Mathematics does not rely on the external world to support or falsify knowledge but on other reference points such as the importance of logic. Science does refer to the external world. The ultimate arbiter of knowledge is empirical (derived from experience) observation. This is not to say that there are not many similarities in the way that mathematical and scientific knowledge are produced; clearly there are. Both disciplines appeal to logic to assess the validity of knowledge claims, but science must also refer to the external, empirical world whereas mathematics does not always need to. Lederman and Niess are careful to note that they are not making judgement claims about which is inherently preferable, but are identifying two very different ways of knowing. They argue that because of these fundamental differences, the disciplinary boundaries between the disciplines should be maintained even when they are being integrated.

These differences in epistemology lead to differences in the ways in which mathematical thinking and tools are used in the two subjects. For example, with graphs in science there is an emphasis on units and variables, as discussed above, because those units and variables are what link the graph to the external world. The context is critical for graphs in science because graphs always represent something specific and thus it is vital to be able to interpret the graph in the light of the phenomena under investigation. The differences in graphing practices thus stem directly from the differences in perspectives between mathematics and science.

The concern of Lederman and Niess (1998) is that much integrated work emphasises inquiry and problem solving. They argue that what counts as data upon which decisions can be made is fundamentally different in the two disciplines and thus attempting to combine them equally will result in a hybrid version of inquiry which is ‘confused and chaotic’ because ‘different disciplines view the world and how one comes to know it differently’ (p. 283). Instead, Lederman and Niess suggest that we should be ‘celebrating the diversity and integrity of the various disciplines, as well as the benefits of differing perspectives’ (p. 284). Rather than trying to dissolve the disciplines and create hybrids we should focus on interactions between them.

3.3.3 Transfer between mathematics and science

In a widely cited study, Bassok and Holyoak (1989) carried out three experiments to look at transfer between isomorphic topics in physics and mathematics: arithmetic progression problems in algebra and constant acceleration problems in physics. The three experiments were carried out with different groups of students: experiment one with 12 9th grade students from a single high school; experiment two with 22 undergraduate college students; and experiment three with 38 9th and 10th grade students from a variety of public and private high schools, all in the US. Students were taught one topic and then given problems to solve in the other domain. Bassok and Holyoak reported that students who had been taught arithmetic progression problems were very likely to be able to use that information to solve constant acceleration problems, whereas there was almost no detectable transfer from those who were first taught the physics topic. Bassok and Holyoak

(1989) asserted that this was because what they learned was very tied up in the physical concepts they were learning about:

> Transfer from physics to other domains is blocked by the embedding of the physics equations within a specific content domain. (p. 161)
>
> In studying physics, students learn that the physical concepts involved in word problems are critical to the applicability of the relevant equations. Accordingly, they do not expect, and fail to recognize, any direct relation between physics problem-solving procedures and isomorphic problems drawn from non-physics domains. (p.165)

Bassok and Holyoak interpreted this to mean that learning in a context results in lower transferability as a result of 'content specific interference' (p. 165).

Bassok and Holyoak's work has led to claims that science instruction provides a context which is content-rich but that is less likely to lead to transfer of skill than mathematics instruction, which is more formal and therefore said to be more domain-independent (Dziembowski & Newcombe, 2005). This claim is somewhat problematic and perhaps even alarming for science educators and it is important to understand the reasons why students may find it easier to transfer learning from mathematics to science than *vice versa*. Transfer occurring only in one direction also has implications for any attempt to improve students' mathematical understanding by an increase in the quantitative content of the science curriculum, as argued for by several authors including Fairbrother (2008).

Dziembowski and Newcombe (2005), however, challenge one of the fundamental assumptions that Bassok and Holyoak make. They argue that the two sets of problems (constant acceleration and arithmetic progression) are not as isomorphic as Bassok and Holyoak contend. They outline in some detail how problems which are amenable to an arithmetic progression solution cannot always be solved by the constant acceleration procedure. They argue that transfer was blocked from physics to mathematics not, as Bassok and Holyoak asserted, because the skills were context-specific, but by the applicability conditions of constant acceleration schemas: a reverse theorem to the mean speed rule is not true. They go on to show that verifying the applicability conditions is only the first step to solving the problem. The student must then find the information needed to begin to use a particular schema from that provided in the problem. If what they need is not there, students must use other mathematical techniques to calculate key variables required and perhaps will not realise that this is potentially the most straightforward method to solving the problem.

As a result, Dziembowski and Newcombe demonstrate that the tests given by Bassok and Holyoak are biased. The constant acceleration in equal time intervals problems are structurally equivalent to the arithmetic progression problems but, importantly, the reverse is not true. It therefore may not be teaching and learning in a context which prevented transfer. Bassok and Holyoak thus do not show that mathematical learning which takes place in science is necessarily harder to transfer. I will return to the topic of transfer in Chapter 4.

3.3.4 Dodd and Bone: Fear and lack of confidence

Dodd and Bone (1995) carried out a study with Key Stage 3 science teachers, mathematics teachers, and pupils in England, to follow up anecdotal reports that students were increasingly struggling with mathematics in science. They argue that science teachers consistently overestimate children's ability in mathematics, with pupils themselves often finding the mathematics in science daunting. They suggest that part of the problem children have in using mathematics in science is a lack of understanding or empathy on the part of science teachers, who simply do not understand how challenging it is for many pupils. Dodd and Bone found the science teachers reported a frequent inability or reluctance on the part of students to transfer their knowledge from mathematics to science. School pupils' difficulties are similar to those reported for undergraduates in higher education (as discussed in Chapter 2), with Yates (2014) likewise noticing a lack of empathy on the part of teaching staff, arguing that academics find it difficult to understand undergraduates' difficulties in using mathematics.

Pupils were aware that they were required to use mathematics within science which they had not been taught in mathematics and this, unsurprisingly, reduced their confidence. Dodd and Bone, both science educators, argue that the problem is not with mathematics teaching, but with both a mismatch in timing between mathematics and science, and science teachers' overestimation of what has been covered in mathematics. They conclude that the mathematical content of the National Curriculum for science is too challenging.

> The inevitable conclusion is that some topics in the KS3 National Curriculum for science implicitly assume a level of mathematics capability which is significantly beyond the majority of pupils. Little wonder that the confidence of pupils in using their mathematics in science is so poor. […] We suggest that the solution is clear:

> such topics should be removed from the KS3 science programmes of study. (Dodd & Bone, 1995, p. 105)

Dodd and Bone end optimistic for the future. Shayer and Adey's (1981) conclusion that much of what is included in science courses for pre-16s is inappropriate seemed to be being heeded, and the Dearing Review (Dearing, 1993) had led to a significant reduction planned in the content of key stage 3 programmes of study, with a number of more mathematical topics being promoted into key stage 4. These changes would currently appear to be being reversed, however, with more mathematics being introduced into science curricula, particularly at GCSE and A-level. Even one of the calls for additional mathematics in science (Science and Learning Expert Group, 2010) admitted that it may be daunting for many students.

Dodd and Bone found that many science teachers wanted closer links with mathematics colleagues in schools, although they did not suggest what these links might look like or what purpose they might serve. There was unanimous agreement among science teachers that 'science and mathematics curricula should be written so that the mathematical skills needed in science are more obviously taken into account' (Dodd & Bone, 1995, p. 104), although no suggestions were given about how this could be achieved.

3.3.5 Pre-service teachers

Czerniak *et al.* (1999) suggested that one way to increase integration would be through teacher education. There are two key studies from initial teacher education programmes which are focused on integrating science and mathematics. In the first, Koirala and Bowman (2003) in a US-based study begin by noting that:

> Many members of the mathematics and science education community believe that the integration of mathematics and science enhances students' understanding of both subjects. Despite this belief, attempts to integrate these subjects have frequently been unsuccessful. (p. 145)

They state that two of the barriers to integration are that teachers lack content knowledge of the other subject and that they have little or no experience of integrating the two. Koirala and Bowman propose to tackle this lack through a joint science and mathematics course for middle school pre-service teachers, giving them the opportunity to take integrated classes. They report that the pre-service teachers appreciated the approach but were concerned that integration was not always a seamless match. Koirala and Bowman report some of the difficulties, including those with vocabulary illustrated through the term *variable*. In science, variables must be operationalised, for example height or temperature; in mathematics variables are often introduced as letters, *x, y, z*, for example, and may not be given a meaning. To their pre-service teachers, integration meant a blending of the two subjects with no visible seams and the authors found it a challenge to persuade them that in their view this is not the case. This is a good example of how difficulties arise when terms such as *integration* are not clearly defined and definitions shared. Koirala and Bowman relate that their course did result in the pre-service teachers having a better understanding of the nature of both science and mathematics.

Koirala and Bowman's findings (2003) also show that not all topics in the science and mathematics curricula integrate easily. They give the example of integers and their operations. In the US, middle school pupils study how positive and negative integers can be added, subtracted, multiplied and divided. Understanding that, for example, the product of two negative numbers is positive is important in mathematics, but rarely so at this level in science. The mathematics pre-service teachers felt they were less well prepared for teaching topics which did not touch on science as they had spent so much time dealing with the topics where the integration was more straightforward. Furthermore, the complexity of the mathematical models required to fully describe some of the science concepts is far beyond the reach of middle school mathematics, further hindering attempts at integration. Once in schools, the pre-service teachers observed very little integration by experienced teachers. However, in spite of the difficulties found by the pre-service teachers following this course, Koirala and Bowman call for continued efforts to integrate and to expose pre-service teachers to integrated methods courses.

Frykholm and Glasson (2005) also work with US pre-service teachers on an integrated course, although those preparing to teach secondary rather than middle school. Similarly to findings from Koirala and Bowman, these pre-service teachers note that although they are on an integrated course, they rarely observe integration taking place when they are in schools. Both the pre-service mathematics and science teachers had concerns about their content knowledge of the other subject. This finding is important to note as it is sometimes expected that science teachers will be comfortable with mathematics, but Frykholm and Glassom report that some of the science teachers recognised gaps in their mathematical understanding. They also lacked pedagogic content knowledge for the other subject, which again made integration more challenging.

To help to overcome this problem the science and mathematics pre-service teachers acted as consultants to each other in teams to plan joint projects. They found that it was easier to begin with a science topic and add in the requisite mathematics than the other way around. This finding reflects those of Pang and Good (2000) discussed earlier. As Frykholm and Glasson acknowledge, a potential difficulty with this approach is that it could lead to mathematics being seen, or even presented, as a set of 'tools for science,' which may not be what the mathematics education community would wish. They raise the question as to what pre-requisite knowledge bases teachers need to have in order to connect mathematics and science, and what experiences best provide that knowledge. As with other authors, Frykholm and Glasson apparently remain convinced that integration is worth pursuing in spite of the difficulties.

3.3.6 Frade *et al.*: A community of practice to teach for transfer

Honey *et al.* (2014) noted that there were very few integrated education programmes where the goal of making connections was stated explicitly, although it was often an implicit aim. One study which is an exception to that is Frade, Winbourne and Braga (2009) which is a largely theoretical paper based on an empirical research project. It uses the idea of communities of practice, exploring the creation of a mathematics-science community of practice in a class taught by Frade, a mathematics teacher, and Braga, a science teacher, to promote transfer of learning between the concepts of proportionality and density, while each remained teaching her own subject.

Frade *et al*.'s primary concern is how boundaries between practices can be crossed by students and, although they do not explicitly say so, teachers. They conceptualise boundaries using Bernstein's ideas of insulated domains or vertical discourses, proposing that:

> Bernstein can help to explain why it is that a major challenge for teachers and students in schools is to do what looks like transfer or boundary crossing. Boundaries may be socially produced but they are no less real for this in the experience of teachers and students. So why is it that some people are so disposed to do what looks like boundary crossing that, for them, boundaries seem to be completely permeable? Why is it that, for others, boundaries have a solidity that makes the very thought of crossing impossible? (2009, p. 17)

Although these questions are not fully answered in the paper, Frade *et al*. begin an interesting exploration of why this might be the case. They were looking to collaborate in an unusual school; as part of the university innovations were encouraged and supported. Thus some key barriers which would exist in many schools (as described by Venville *et al*., 2002, and discussed above) were not present, or were present to a lesser degree than in many other schools.

One aspect which stands out in Frade *et al*.'s study was the time that the collaboration took. They report that it took many hours of conversation to set up, on average two hours per week for five months, just to teach one topic each which involved four class-hours for mathematics and eight class-hours for science. In this time they shared the materials that each would use and explicitly tried to bring together the language codes of the disciplines, discussing how and when bridges could be built. The insulation between the disciplines contributed to just how difficult it is to build bridges between them.

These were two teacher-researchers, with enough interest in each other's disciplines to want to bridge the gap, and it still took considerable time and effort to understand the differences and similarities between them. Their findings reflect the conclusions of both Frykholm and Glassom (2005) and Koirala and Bowman (2003) that lack of content knowledge and pedagogic content knowledge of the other subject is a barrier to collaboration. Setting up the community of practice involved understanding the differences, which they followed with changes in their discursive practices; each of them deliberately choosing to use language which reflected that of the other teacher as they made 'efforts explicitly to bring together the language codes of the disciplines, and discussions of how and when bridges could be built' (Frade *et al*., 2009, p. 18). There was a change in transmission practices, too, with the inclusion of a section of work on 'special ratios' in mathematics which included examples from science such as speed. As what is reported is a one-off project, it is not clear whether this huge time commitment would need to be repeated for any further pair of topics in which the authors tried to link their teaching.

Frade *et al*. (2009) explicitly cited the goal of increased transfer as the reason why they attempted to set up a mathematics-science community of practice. The evidence that they present for its success is not extensive and comprises one or two pupils seeing the links and then discussing and sharing them with the class. In spite of this paucity of evidence they propose that although there may be disjuncture between practices and discontinuities of meanings across boundaries it may be possible to bridge the gaps by identifying areas where there might be overlaps. Further, they suggest that it is possible to demonstrate how the teacher can provide a structure in the school discourse to allow transfer. They argue that:

> Transfer is a process that does not result automatically from learning. Transfer is seen as something that can be, and needs to be, taught if the aim of teaching is to help students to make connections between semiotically and conceptually different practices. (2009, p. 16)

Frade *et al*. propose that transfer of knowledge is a:

> practice which can be opened up to students – but that it depends, essentially, on a mode of teaching that encourages students to make parallel investments: in their mathematical identities, in their development of their knowledge, and in their participation in the practice. (2009, p. 16)

Importantly, they argue that transfer is strongly linked to the predisposition to learn rather than a parcel of knowledge carried from place to place; that transfer occurs by developing an identity which predisposes individuals to look for and make use of mathematical knowledge in a range of contexts. It helps to explain why it is that some students are disposed to do what looks like boundary crossing, in contrast to the majority. If a student identifies as a 'mathematical person' then they will look for mathematics and ways to apply mathematics in situations outside their mathematics lessons. Research into both transfer and identity is discussed further in Chapter 4.

3.3.7 Zhang *et al.*: Students' use of mathematics in science

Zhang, Orrill and Campbell (2015) argue that 'mathematics and science share a coherent set of values and concepts' (p. 358) including problem solving and process skills. Like other authors, in the search for similarities they tend to ignore the differences in epistemologies between the disciplines outlined, for example, by Ledermann and Niess (1998). Interestingly, Zhang *et al.* relate the need for integrating mathematics and science to research that has shown that novices in a domain typically lack a coherent mapping of that domain and tend to only see surface features rather than understanding the interrelations. They link this lack of coherent mapping with the idea that knowledge is developed and organised in a fine-grained manner resulting in individuals' knowledge and understanding being invoked in different ways in different situations, and suggest that this is why students who can draw graphs in mathematics may struggle to do so in science. Zhang *et al.* suggest that:

> The content of both science and mathematics should encourage teachers to integrate and use new knowledge and skills from across areas of competence. While it may be relatively easy for teachers to find points of overlap in the content of mathematics and science, it may be more difficult for them to identify the overlapping skills and dispositions students will need in these contexts. (2015, p. 358)

Suggesting it is easy for teachers to find points of overlap presupposes that teachers are able to see these connections, which would require the content knowledge of both subjects and an understanding of the connections within and between them. Having the knowledge and appreciating the connections is recognised as being hard in only one of the subjects (Turner & Rowland, 2011); seeing it across two disciplines when the teacher probably teaches in only one is unlikely to be easy.

The aim of Zhang *et al.*'s research was to use Rasch analysis to map and compare the knowledge resources 516 15-year-old Chinese students used across mathematics and science PISA assessment items, in order to explore the extent to which their knowledge of the two is connected. Their analysis revealed no clear evidence for students conceptualising the domains in linked ways as they were using different strategies for mathematics and for science items. Zhang *et al.* offer two possible explanations for their findings. One is that the mathematics items they selected did not overlap sufficiently with the science contexts and thus there was a problem with the design of the research. The other is that students see mathematics and science as two separate fields and do not have many knowledge resource connections between them. They suggest that interviews carried out alongside testing using the items could help to explore both possibilities further. It is an interesting study, in part because there is so little research into how students use mathematics within science.

Scott (2012) also gave students mathematics and quantitative science (in his case, chemistry) questions and compared student responses. His sample was 58 16-17 year olds in Scotland, with eight science and eight apparently analogous mathematics questions. He asserts that students' difficulties in solving quantitative chemistry questions is the fault of mathematics teachers and teaching. Perhaps instead, the studies of Zhang *et al*. and Scott, together with Dziembowski and Newcombe's (2005) critique of Bassok and Holyoak's (1989) study, demonstrate that it is very difficult to set test items of mathematics and science questions which are genuinely analogous in order to make comparisons between them.

3.3.8 Language of physics; language of mathematics

Redish and Kuo (2015), US university physics lecturers, ask in a reflective essay why it is that so many physics undergraduates struggle to use mathematics within physics, even when they may have achieved considerable success in mathematics courses. Like other authors such as Scott (2012), they suggest that sometimes this is because students struggle with basic mathematical concepts. However, they use ideas from linguistics research to argue that the difficulty is more subtle and lack of mathematical understanding is often not the real problem. They suggest that symbology is used to make meaning differently in mathematics and science and consequently that the formal syntax is very different:

> Although the formal mathematical syntax may be the same across the disciplines of mathematics and physics, the uses and meanings of that formal syntax may differ dramatically between the two disciplines. These differences in meaning may be masked by a similarity in the formal syntax. (p. 562)

By this they mean that although the mathematics looks the same, it is used and interpreted differently and for different purposes. Mathematics is about expressing abstract relationships. In physics, physical knowledge about actual systems is blended into the equations and mathematics, which significantly changes their interpretation.

> The key difference is that loading physical meaning onto symbols does work for physicists and leads to differences in how physicists and mathematicians interpret equations. We not only *use math in doing physics*, we *use physics in doing math*. (p. 563, italics in original)

As a result, they argue, mathematics in physics has a different semiotics (the way meaning is put into symbols) than mathematics as used by mathematicians. Loading physical meaning onto symbols (for example by giving them units or appreciating the logical limits of what those symbols stand for) allows physicists to use more straightforward mathematics than would be used in the same situation by a mathematician. Physicists also blend physical meaning into the mathematics by 'filtering the equation through the physics' (p. 565).

> The culture of physics expects that each symbol in an equation is to be interpreted in conjunction with its physical meaning. So, part of the acculturation of a physics

> student is learning to interpret the math physically, not to only focus on mathematical structure and manipulations. (p. 567)

This is not the case for mathematics as usually the symbols are not tied to physical meaning.

> In the culture of physics, the use of mathematical expressions is complex, because the ancillary physical meaning of symbols is used to convey information omitted from the mathematical structure of the equation. This is because we have a different purpose for the math: to model real physical systems. (p. 567)

Redish and Kuo argue that this use of mathematics within physics for different purposes to those in pure mathematics amounts to mathematics-in-physics being akin to a different dialect of mathematics, or a different-but-related language. Physics undergraduates need to learn not just mathematics, but how the discipline of physics *uses* mathematics. These differences are obscured by apparent similarities of the two, but in reality most students will require additional support to learn the language. This is perhaps related to the finding from Grove and Pugh (2015) discussed in Chapter 2, that chemistry students can be supported to learn the mathematics they need for their undergraduate degree and, crucially, that this is more likely to be successful if they are taught within the chemistry department by chemistry lecturers. In other words, chemistry students have more need to learn mathematics-in-chemistry than pure mathematics and they learn it best from someone who speaks ‘mathematics-in-chemistry’.

These language differences may also be part of the reason why students at school level can find it difficult to use mathematics within science. The differences in how mathematics is used and interpreted, for example by having units with almost every number and those units conveying physical meaning, could contribute to making the transfer of knowledge between the disciplines less straightforward than teachers sometimes assume.

3.3.9 Mathematics in science: *School Science Review*

In 2016 the ASE’s in-house journal *School Science Review* had a themed issue on mathematics in science. In the editorial it is explained that this theme was in response to the greater prominence given to mathematics in the most recent science curriculum and concerns from teachers regarding transfer (Needham, 2016).

In spite of this identified concern about transfer, none of the articles in the theme issue cite any existing transfer research. Indeed, across all the articles there are very limited citations of any prior research, including into mathematics in science or the relationship between the disciplines. Most have very few references cited at all and many of those which are cited are curriculum documents. As a result, while there are good points raised by many of the papers, there is very limited theorising about why students find it difficult to use mathematics in science and how they can be helped to do so more effectively.

Millar (2016) argues that the way that statistics is taught in biology has not kept up with modern statistical methods, with students being asked to learn obsolete and even incorrect methods. This is not simply due to teachers being out of date, but extends beyond as:

> The quality of statistical literacy of those who write the government requirements, the specifications, the examinations, and the textbooks leaves much to be desired. (Millar, 2016, p. 29)

Millar does not say so, but this is clear evidence of a disjoint between the writers of the biology and the mathematics, or statistics, curriculum.

Warren (2016) discusses the pH scale and suggests that students would better understand it if the underlying mathematical principles were developed alongside practical investigations. At key stage 3 (age 11-14) this could mean including negative numbers on the pH scale. She suggests that at age 15-16 the mathematical derivation of the expression $[H^+]=10^{-pH}$ should be included:

> The derivation of this expression is something that 15- to 16-year-old students should be able to follow, as it is most likely they will have covered all the mathematical ideas within the mathematics curriculum. However, we cannot presume that they will be able to transfer the mathematical concepts into the chemical context and so further explanation may be required. (Warren, 2016, p. 39)

In reality, it seems likely that the vast majority of students would find this difficult, not least as they would not have covered the use of square brackets to mean concentration and most, if not all, would not have covered negative indices.

At A-level (16+) students need to understand that $pH = -\log_{10}[H^+]$. Warren notes that:

> Many students do not fully understand logarithms (logs) or appreciate logarithmic scales […] even a basic understanding of logs will help students to understand some chemical concepts more fully. (Warren, 2016, p. 41)

What she does not make clear, however, is that students who are not doing A-level mathematics will not have covered logs or logarithmic scales, and even those who are doing A-level mathematics may not have met logs prior to their use in chemistry. While what she has to say about understanding the mathematics leading to a greater understanding of the chemistry is undoubtedly true, she skims over the problems that introducing and explaining this mathematics is likely to cause in the chemistry classroom.

Thompson (2016) argues that student progress is linked to understanding the transferability of skills rather than just on getting the right answer. He notes teacher frustration when students do not transfer their knowledge:

> The phrase ‘transferable’ is given to skills that can be applied across a variety of subjects and contexts and teachers are often frustrated when they hear that students ‘can do it’ in maths but ‘can’t do it’ in physics, or ‘could do it when we studied energy but can’t do it with forces’. (2016, p. 44)

Yet he does not cite any of the literature on transfer and thus does not theorise why students might find transfer difficult. He states that there is limited transfer even between science topics due to lack of understanding of the underlying mathematics.

Southall (2016), a mathematics educator, suggests that students are often taught shortcuts in mathematics classes rather than full understanding. These types of methods, he suggests, bypass understanding, making it harder for students to appreciate if their answers are likely to be correct and reducing their mathematical confidence. He also argues that the lack of understanding is behind many students’ dislike of mathematics. Southall makes some good points, but once again they are not tied to the existing literature on procedural teaching, understanding and transfer by authors such as Boaler (2002) or Boaler and Greeno (2000). The work of Boaler on transfer and identity is discussed in more detail in Chapter 4.

3.4 Questions arising

Thus far we have seen that there are a limited number of empirical studies on the relationship between school science and mathematics education. There is a particular dearth of research on collaborations which arise organically in schools. There are difficulties with terminology, with a lack of agreed definitions for some key terms which are widely used, such as integration, making it difficult to compare research from different authors. There is limited research on students’ use of mathematics within science and why it is that many find it difficult. Some papers which are published do not theorise reasons for the difficulties and cite few, if any, examples of prior work in the field. More recent research by authors such as Williams *et al.* (2016), Redish and Kuo (2015), and Frade *et al.* (2009) is beginning to provide a more rigorous theoretical framework to describe the difficulties encountered when working across the boundary of science and mathematics.

Those who promote some form of collaborative or integrative work tend to believe that it will have beneficial effects for the students, in spite of scant evidence to support this hypothesis (for example, Venville *et al*., 2002, and Koirala & Bowman, 2003) . Some of the claimed benefits are very nebulously defined such as improving STEM literacy (Honey *et al*., 2014). Others include increasing student interest and engagement (for example, Venville *et al*., 2002, Honey *et al*., 2014) which can also be difficult to measure. Another claimed benefit is to help students to apply what they have learned in one context to another, often called transfer (for example, Frade *et al.*, 2009, Scott, 2012, Honey *et al*., 2014).

In spite of the calls for closer connections between the subjects at school level, collaboration does not seem to be common, at least in England. Successive reviews of the literature have rehearsed many reasons why this may be the case, some focusing on the pragmatic, such as lack of knowledge of content and curricula of the other subject, and others looking beneath that and suggesting that working together requires the confrontation of power structures, questions of identity, and differences in discourse. In the English curriculum the subjects are kept separate and the national curriculum does not show or promote links between them.

From the above analysis, I have identified questions as yet unexplored, or under-explored, in the literature. I note the limited discussion about power and thus ask:

1. What are the power structures and differences in discourse and practice which school mathematics-science collaboration confronts?

I pick up on the role of national education policy in informing science education practice in schools as discussed by Fensham (2009), and the role of curriculum policy in influencing the relationship between mathematics and science departments as hinted at by Dodd and Bone (1995), and thus ask:

2. How is the English national curriculum produced and by whom? What are the influences and ideologies behind the curriculum? Have they remained constant over time?

I consider that transfer is inadequately discussed, particularly as improving transfer is a suggested benefit to working collaboratively (Frade *et al*., 2009, Honey *et al*., 2014), and I therefore ask:

3. What is transfer between disciplines? How is it conceptualised and why is it widely recognised as being a difficult thing to do? Is there evidence that closer collaboration between the disciplines can help students to transfer? Can transfer be taught?

Finally, I follow up on the hint in the review by Williams *et al*. (2016) that it is important to consider teachers' identity and note the enduring belief in collaboration even by those who have identified considerable practical difficulties in its enactment. I thus ask:

4. How do identity and beliefs have an impact on teachers' curriculum decision making?

The body of literature specifically about mathematics and science collaboration is small. In the next chapter, I turn to the wider education, sociology and psychology literature to seek some answers to the above questions.

Chapter 4
The wider literature and a theoretical framework

In this chapter, I will review the wider education, sociology and psychology literature which can shed light on the questions arising from Chapter 3, namely:

1. What are the power structures and differences in discourse and practice which school mathematics-science collaboration confronts?
2. How is the English national curriculum produced and by whom? What are the influences and ideologies behind the curriculum? Have they remained constant over time?
3. What is transfer between disciplines? How is it conceptualised and why is it widely recognised as being a difficult thing to do? Is there evidence that closer collaboration between the disciplines can help students to transfer? Can transfer be taught?
4. How do identity and beliefs have an impact on teachers' curriculum decision making?

In so doing, I will develop the theoretical frameworks which will be used to guide the research and data analysis.

4.1 Boundaries, borders and power structures

4.1.1 Creating and perpetuating boundaries

A number of the papers and studies reviewed in the previous chapter were concerned with the borders and boundaries that exist between mathematics and science departments in schools. Two of these (Venville *et al*., 2002 and Frade *et al*., 2009) turned to the writing of Bernstein to explore the nature of these boundaries and what is required to cross them. Frade *et al*. suggest that:

> Bernstein can help to explain why it is that a major challenge for teachers and students in schools is to do what looks like transfer or boundary crossing. Boundaries may be socially produced but they are no less real for this in the experience of teachers and students. (2009, p.17)

Indeed, in a review of border research more broadly, including both geographic and social borders, Newman argues that: ‘all borders are social constructions, delimited and demarcated by people’ (2003, p. 17). Startlingly he also suggests that crossing:

> the language barrier of the borders between academic disciplines and practitioners is often harder than the trans-boundary movement which is increasingly taking place across the borders between states. (*ibid.* p. 16)

For both Newman and Bernstein, boundaries are created by, and closely associated with, the operation of power. Bernstein argues that:

> Power relations […] create boundaries, legitimise boundaries, reproduce boundaries, between different categories of groups, gender, class, race, different categories of discourse, different categories of agents. Thus, power always acts to produce dislocations, to produce punctuations in social space […]
>
> Power always operates on relations *between* categories [*in this thesis, categories are discipline groups at policy level or subject departments*]. The focus of power from this point of view is on relations *between* and, in this way, power establishes legitimate relations of order. (Bernstein, 2000, p. 5)

To look at the relation between categories (here, subjects, A, B & C), Bernstein uses the idea of classification. To him, classification refers to the relation between categories. He argues that in order for categories (subjects) to be differently specialised from each other they need a space in which to develop their unique identity. This space is not within the subject itself, but in the distance which separates one subject from another. In order to be differently specialised ‘they must have a space in which to develop their unique identity, an identity with its own internal rules and special voice’ (p. 6). He argues that the crucial space which allows the specialisation:

> is not internal to that discourse but it is the space between that discourse and another. In other words, A can only be A if it can effectively insulate itself from B. In this sense, there is no A if there is no relationship between A and something else. The meaning of A is only understandable in relation to other categories in the set […] It is the insulation between categories of discourse which maintains the principle of their social division of labour. In other words, it is silence which carries the message of power; it is the full stop between one category of discourse and

> another; it is the dislocation in the potential flow of discourse which is crucial to the specialisation of any category.
>
> If that insulation is broken, then a category is in danger of losing its identity, because what it is, is the space between it and another category. Whatever maintains the strengths of the insulation, maintains the relations between the categories and their distinct voices. (Bernstein, 2000, p. 6)

In other words, the identity of one subject is reliant on it being different from, separated from, insulated from another subject. Science can only be science if it can effectively insulate itself from mathematics; mathematics can only be mathematics if it can effectively insulate itself from science. If the insulation between the categories is broken then it can become impossible to tell where one ends and the other begins and they are in danger of losing their unique identity.

Newman similarly argues that:

> The essence of a border is to separate the “self” from the “other.” As such, one of the major functions of a border is to act as a barrier, “protecting” the “us insiders” from the “them outsiders”. (2003, p. 14)

Bernstein uses the concept of classification to examine relations between categories. His use of classification is distinctive and refers to the relations between categories, with strong classification meaning strong insulation (his term) between categories.

> In the case of strong classification, each category has its unique identity, its unique voice, its own specialised rules of internal relations. In the case of weak classification, we have less specialised discourses, less specialised identities, less specialised voices. But classifications, strong or weak, always carry power relations. (Bernstein, 2000, p. 7)

Where classification is strong the boundaries between subjects are strong and the subject is well insulated from others. The insulation between mathematics and science in school is produced by differences in discourse and language, by specialised teachers, by specialised teaching spaces and support staff. When classification is weak the insulation between subjects is weaker and it is less clear where one subject ends and another begins. In school, the boundaries between the sciences – biology, chemistry and physics – are reasonably strong; the boundary between science and mathematics even more so.

Bernstein argues that the consequence of strong boundaries is a dislocation, or break, in the transmission of knowledge:

> Strong classification of discourse is likely to lead empirically to a dislocation in the transmission of knowledge because, with strong classification, the progression will be from concrete local knowledge, to the mastery of simple operations, to more abstract general principles, which will only be available later in the transmission. (2000, p. 11)

In other words, strong classification of subjects will make it harder to use knowledge learned in one subject in a different subject. Bernstein here argues that strongly classified subjects will begin with concrete knowledge which is 'local' or tied to the subject. It is the 'more abstract general principles' which can more easily be used elsewhere. He goes on to explain that children who do not do well at school are likely to remain learning only the simple operations and that such knowledge is impermeable – it cannot be used elsewhere. It is only those who are successful and therefore learn the more abstract general principles who may become aware of the arbitrary nature of the distinctions between the subjects, and not all of those will do so. Bernstein argues that:

> The arbitrary nature of these power relations is disguised, hidden by the principle of the classification, for the principle of the classification comes to have the force of the natural order and the identities that it constructs are taken as real, as authentic. (Bernstein, 2000, p. 7)

In other words, the differences between science and mathematics are taken as real and authentic, although they are, in reality, arbitrary.

Although the boundaries may be strong, Newman argues that:

> Borders are […] there to be crossed. From the moment they are established, there are always groups who have an interest in finding ways to move beyond the barrier. (2003, p. 14)

While 'relatively little attention has been paid to the way in which borders are opened or may be removed altogether' (*ibid.* p. 20), he cautions that 'crossing the border does not always bring the expected benefits' (*ibid.* p. 14).

4.1.2 Departmental boundaries

4.1.2.1 Departments and status

Subject departments have been an almost ubiquitous feature of secondary schools since they first appeared in the early years of the 20th century but understanding them and their influence has only been the subject of research in the last two decades (Melville, Campbell, & Jones, 2016). From her studies of schools in the USA, Siskin (1994, p. 5) suggests there are four critical aspects to subject departments: they act as strong boundaries in dividing the school; they provide the site of teachers' primary social interaction in schools, for professional identity and community; they have considerable power over what and how teachers teach; and, as a knowledge category, they influence the decisions and shape the actions of the teachers who are a part of them. She argues that, for teachers, departments are a key part of their identity and an important aspect of secondary or high school life.

> [To] teachers, the department is highly visible, and central to understanding the complex workings of their schools: important to who they are, consequential in affecting what they do, and largely determining how their work is perceived. (Siskin, 1994, p. 8)

Ball, also from detailed studies in schools, agrees that in England, aside from pastoral care, 'subject departments are usually the most significant organisational divisions between teachers as colleagues' (1987, p. 222).

Within schools, different departments have different status, with the academic subjects holding high status as 'what you go to school for' (Siskin, 1994, p. 125). In England the high status subjects include English, mathematics and science. These subjects are all explicitly included in the government's accountability measures and so given high status nationally no matter what the struggles are of the department within the individual school. Ball, however, maintains that 'external legitimation […] is just one factor in affecting the standing of departments and teachers' (1987, p. 230).

School departments are usually led by a head of department (often referred to as a Chair in North America) and Bernstein (2000) suggests that in a strongly classified system, it is the heads of department who will relate to each other. Ball (1987) noted that relationships between departments are not always peaceful and likened the frequent conflict between them to those between English barons in the middle ages; essentially concerned with wealth and power. For the heads of department conflict is in terms of budget allocations, staffing, timetable time and control of territory such as teaching rooms, offices and special facilities.

> Conflicts over access to scarce resources – time, personnel, capitation, territory and pupils, or at least particular varieties of pupils – are enjoined between departments. (Ball, 1987, p. 42)

Science has a clear head start in these struggles as in most schools the science department has its own specialised laboratories which are not commonly shared with other staff, prep rooms and specialised support staff – lab technicians. With the need to fund practical work, science usually has the largest department budget in English secondary schools even before the extra staffing is taken into account. These specialised facilities help to maintain the insulation between science and mathematics departments.

Subjects with high status are more likely to attract high status students, those who are expected to or who have achieved high grades in external examinations. Ball (1987) argues that partly what departments are fighting for is access to the highest status students, particularly post-16. According to Goodson, ‘the close connection between academic status and resources is a fundamental feature of our educational system’ (1995, p. 173). Thus departments with high status attract more funding which is consequently channelled to the higher status students.

4.1.2.2 Departments and breaks in communication

Bernstein (2000) suggests that where there is strong classification, teaching staff are tied to their departments and that their identity is bound up with that of the department. He gives two reasons for this phenomenon: firstly, ‘the department is symbolic of their category’ and, secondly, promotion comes by appropriate activities in the department (p. 10). Ball (1987) observed in practice that for many secondary teachers their subject, and their commitment to it, is a key part of their overall commitment to teaching. Being a *subject* teacher is central to the satisfactions that they achieve from their work. Indeed, the selection criteria for initial teacher education include enthusiasm for the subject to be taught (University of Oxford, 2016).

Teacher identification with the subject goes beyond the enthusiasm for what they teach. Siskin noticed that secondary teachers of different departments speak quite different languages and:

> demonstrate the distinctive vocabularies, logics, and concerns of their subject specialities in subject-specific ways […] these are more than simply idiosyncratic appearances of technical jargon; rather the discipline's language and epistemology are interwoven in the ways teachers – as subject-matter specialists – conceptualise their world, their roles within it, and the nature of knowledge, teaching, and learning […]
>
> Teachers frequently explain who they are, what they do, or how they do it by anchoring their identities, actions and understandings in the subject matter itself […]
>
> Even when teachers do not directly reference the subject matter, disciplinary background reveals itself in the choice of words, the structure of their arguments, or the goals they hold. (Siskin, 1994, pp. 152-153)

Ball argues that there are differences between subjects in their views about the broader purposes of education, about how children learn and about the classroom responsibilities of the teacher and that these 'complexes of epistemological, pedagogical and education values and assumptions constitute, in each case, a subject sub-culture' (1987, p. 41). The same was found to be true in the USA:

> Teachers of different subjects bring differing frames of reference to their teaching; these subject-matter frames […] inform teachers' thoughts and actions. (Grossman & Stodolsky, 1995, p. 8)

The consequences of this are explained by Bernstein who argues that when subjects are strongly classified:

> the staff cannot relate to each other in terms of their intrinsic function, which is the reproduction of *pedagogic discourse*. Where the lines of communication between staff are established by a system of this kind, there will be weak relations between staff with respect to pedagogic discourse, as each is differently specialised. (2000, p. 10)

In other words, differences in language and discourse between departments result in breaks in communication leading to weak relations between staff from different departments.

4.1.3 Power structures, change and innovation

Ball argues that ‘where relationships between teachers are poor almost any attempt at innovation can be seen in terms of the political motivations or career aspirations of the instigators’ (1987, p. 227). Thus, unless the relationship between the departments is good in the first place, a science or mathematics department trying to collaborate might very well be viewed with suspicion. It would perhaps be easier for technology departments, which are traditionally much weaker and therefore unlikely to be perceived as a threat within the power structures of the school, to reach out and work with either science or mathematics than for science and mathematics to work with each other. Departments which feel threatened in some way, for example by having difficulties in recruiting and retaining appropriately qualified staff or by having poorer than expected results in high stakes tests, are less likely to reach out and try to coordinate with another department – especially if they perceive that department to be in some way a threat. Under these circumstances they are more likely to want to preserve the boundaries around their department and keep their territory secure. This observation might apply to either science or mathematics departments.

Bernstein argues that ‘attempts to change degrees of insulation reveal the power relations on which the classification is based and which it reproduces’ (2000, p.7). Collaboration between departments might result in a change in the insulation between them and thus, according to Bernstein, a number of other changes will happen as a result:

> Changes in organisational practices, changes in discursive practices, changes in transmission practices, […] changes in the concepts of the teacher, changes in the concepts of the pupils, changes in the concepts of knowledge itself. (2000, p. 15)

If this is indeed the case, it explains why innovation will be strongly resisted by those who feel in any way threatened even prior to the proposed change.

Venville *et al*. (2002) suggest there is a resistance to change in schools caused by a ‘grammar of schooling’ which underpins the culture of schools, reinforced by the customs and artefacts of everyday school life – such as the timetable and the organisation of schools into departments. Once established, this ‘grammar of schooling’ is difficult to change. In a country with a high level of government control of schooling, or even a strongly dominant culture of schooling, it might be expected that most schools would be broadly similar. They point to many factors which can contribute to the strength and persistence of this ‘grammar of schooling’ or school culture including teacher recruitment and identity, assessment structures particularly for high stakes testing, subject status and a content-laden curriculum.

Change, or innovation, can arise in a variety of ways but Ball (1987) identifies the headteacher as a crucial factor. It is the head who usually introduces change into the school and even where this is not the case the support of the head is necessary for any innovation proposed by a member of staff (Ball, 1987). The head can also be critical in resistance to change. The head can block, stifle, dissuade or ignore groups in school who advocate innovation. According to Ball, 'The character and quality of the headteacher are by far the main influences in determining what a school sets out to do and the extent to which it achieves those aims' (1987, p. 82). The key role that the headteacher and senior leadership team play was also identified by Straw, MacLeod and Hart (2012). They found that change in practices within and between STEM departments proved difficult in schools where that innovation did not feature among senior leaders' priorities or have their support.

While the importance of role of the headteacher is generally undisputed, just how much power they have in reality is a matter of debate. The National Curriculum is followed by most schools in England; in academies, heads may be answerable to the sponsors or academy chain and in all schools there are governing bodies who wield varying amounts of power. As well as outside influences on the school, there are internal ones too. 'The head must achieve and maintain control […] while encouraging and ensuring social order and commitment' (Ball, 1987, p. 82). The head's power can pass to other actors within the school. The amount of autonomy individual teachers and, especially, heads of department have to initiate change in their departments may be affected by the style of the headteacher and their relationship with those staff members. Some heads grant their heads of department considerable autonomy to run their department how they wish. In practice there are certain areas that heads tend to leave to their heads of department; few heads 'infringe in any direct way on those areas of subject expertise (pedagogy and curriculum) that are traditionally regarded as the province of the department' (Ball, 1987, p. 40).

Were a teacher to wish to work collaboratively across science and mathematics, they would need to have their head of department on side, as well as the headteacher and the head of the other department. In a busy school, getting this much agreement between parties could prove a significant barrier. Then there may be other staff to convince if the collaboration is not to be confined to a very small number of teachers. This process can begin to threaten other interests:

> The introduction of, or proposal to introduce, changes in structure or the working practices must be viewed in terms of its relationship to the immediate interests and concerns of those members likely to be affected, directly or indirectly. Innovations are rarely neutral. They tend to enhance the position of certain groups and disadvantage or damage the position of others. Innovations can threaten the self-interests of participants by undermining established identities, by de-skilling and therefore reducing job satisfaction. By introducing new working practices which replace established and cherished ways of working, they threaten individual self-concepts. Vested interests may also be under threat: innovations not infrequently involve the redistribution of resources, the restructuring of job allocations and the redirection of lines of information flow. (Ball, 1987, p. 32)

Teaching across science and mathematics is difficult because of the huge amount of both subject knowledge and subject-specific pedagogical content knowledge which are required. Requiring this way of working can undermine teachers' established identities and make them feel de-skilled (Ball, 1987), leading to a reduction in job satisfaction. When there is an acute shortage of mathematics teachers (Weale, 2015), as well as a shortage of physical science teachers, headteachers and heads of departments may be understandably wary of reducing teachers' job satisfaction in case they move on. Thus the take-up of a suggested innovation, for example science and mathematics teachers working collaboratively, may be resisted, even if there are apparently very good reasons for them to do so.

> Outcomes, in terms of curriculum change, cannot be assumed to be the result of rational, bureaucratic procedures. The departmental barons will not concede control easily. To a great extent, change or resistance to change will depend upon the relative influence of protagonists over organisational decision-making (Ball, 1987, p. 230).

Thus the person or people proposing a change in working practices must have sufficient influence within the school to be able to make the change happen. Change, and particularly large-scale and/or sustained change, is therefore most likely to come from those with a reasonable amount of power within the organisation who are able to have their voices and views heard and acted upon.

For Bernstein, change or resistance to it is related to the strength of the classification, the strength of the boundaries between departments. He argues that when classification changes it is important to ask in whose interest is that change:

> Where we have strong classification, the rule is: things must be kept apart. Where we have weak classification, the rule is: things must be brought together. But we have to ask, in whose interest is the apartness of things and in whose interest is the new togetherness and the new integration? (2000, p. 11)

Bernstein later proposes that if classification changes from strong to weak, as would be the case when departments begin to collaborate, there are questions which should be asked:

- Which group is responsible for initiating the change? Is the change initiated by a dominant group or a dominated group?
- If values are weakening, what values still remain strong? (2000, p. 15)

4.1.4 Summary

Thus we have seen that power operates to produce what Bernstein calls dislocations in social space, producing and reinforcing boundaries between departments. There are many factors which contribute to this insulation including differences in language, teacher identification with their departments and vested interests fighting for access to scarce resources. While these boundaries may be socially produced it does not make them any easier to cross and they have been described theoretically and observed in practice by a number of authors. The insulation is such that science and mathematics teachers have different discourses, not only in terms of their original subject specialism but also different epistemologies, pedagogies and educational values which inform teachers' actions. Bernstein argues that 'A can only be A when it can separate itself from B' (2000, p. 6). Breaks in the insulation between subjects, and changes in working practices, can lead to loss of power and status within the school. As departmental status is essential in gaining access to funding and attracting high status students this is not a minor consideration. When examining innovations which change the classification it is therefore important to consider who is initiating the change, whether they are dominant or dominated, and who benefits.

4.2 Ball, policy and transformation

As we saw in Chapter 1, Fensham argues that 'much science education research takes place as if school science exists in a political and cultural vacuum' (2009, p. 1080). He suggests that education policies are operational statements of values, with values and authority providing the link between policy, research and practice. He suggests that in any discussion of policy, the following questions should be asked:

- Whose values about science education are favoured by this policy?
- Which stakeholders in society have been successful in the shaping of this policy?
- Which groups in society will be advantaged and which disadvantaged by the science education practices that flow from this policy? And additionally,
- Are disadvantaged groups favoured in our studies of practice and would others be disadvantaged if policy was framed to support our practices? (*ibid.* p. 1081)

The term policy is commonly used but difficult to define (Hill, 2013). Ball suggests policy is 'a process, something on-going, interactional and unstable' which is often 'messy, contradictory, confused and unclear' (2013, p. 8). In this section, I ask what the influences and ideologies are behind an example of a policy document, the national curriculum, after first considering how a school curriculum relates to the academic discipline which shares its name.

4.2.1 The transformation of academic discourse to school subjects

A school subject is not the same as the academic discipline to which it is related. Stengel (1997) gives the simplest definition of a school subject as something which is taught in school. Each of the sciences and mathematics are academic disciplines which cannot be taught in schools without being suitably adapted for this different purpose. The methods and circumstances of these adaptations help to create the spaces or insulation between the subjects.

Bernstein (2000) suggests other discourses are selectively appropriated, relocated, refocused and related to other discourses to constitute the new pedagogic discourse, or school subject, a process he calls recontextualisation. Note that it is plural – other discourse**s.** Material may be drawn from more than one academic discipline to constitute a school subject. For example, school chemistry comes from the academic disciplines of chemistry, geology and material science among others. This pedagogic discourse is not the same as the academic disciplines:

> Pedagogic discourse is not physics, chemistry or psychology. Whatever it is, it cannot be identified with the discourses it transmits. (Bernstein, 2000, p. 32)

The selecting and refocusing of mathematical content is different for school mathematics and for school sciences as the discourses which are being produced are different, the ideology is different and the theories of instruction are different. These differences in selection, refocusing and ideology begin to explain how something viewed at a higher level as the same idea, such as density and proportionality (as investigated by Frade *et al*., 2009), come to look very different when re-contextualised into different discourses. The original discourses, in this case the academic disciplines of physics, mathematics, chemistry, biology, are taken from what Bernstein calls their 'original site of effectiveness' (1996, p. 47) to a pedagogic site. As this happens a gap is created between the original and the pedagogic, and ideology can operate in that gap:

> As the discourse moves from its original site to its new positioning as pedagogic discourse, a transformation takes place […] because every time a discourse moves from one position to another there is a space in which ideology can play. No discourse ever moves without ideology at play. (Bernstein, 2000, p. 32)

This appropriating is not usually done by those who are active in the academic field, but those who work in the field of recontextualisation: textbook authors; the writers of curricula; teachers. The authors of school physics textbooks, or physics curricula, for example, are rarely practising physicists. Those doing the recontextualising will select from the totality of the academic discipline of physics and, critically for this thesis, also select how the school subject will relate to other subjects.

> There is a selection in how physics is to be related to other subjects, and in its sequencing and pacing. (Bernstein, 2000, p. 34)

The recontextualisation may occur at a national level, for national curricula, formal examinations or inclusion in textbooks, or at a local, individual teacher or school level. While decisions about sequencing and pacing, both at national and local level, may sound neutral and likely to be value free, they can have significant consequences, as I will demonstrate. The key point from the perspective of the relationship between science and mathematics is that this recontextualising happens separately for each separate pedagogic discourse. There are different recontextualising agents (people) for mathematics and for science and usually, at secondary level, for each separate science. At a national level, these people each select how their subject will be described and how it will be related to other subjects. Content from other discourses is refocused to produce the particular pedagogic discourse.

Similar to Bernstein's idea of recontextualising knowledge, and more popular on mainland Europe, is the theory of didactic transposition. Didactic transposition is the modification of knowledge for instructional purposes. The theory is based on the idea that bodies of knowledge are, with a few exceptions, designed to be used rather than taught (Kang & Kilpatrick, 1992). Most of what is taught in school is generated outside the school and is moved into school out of a social need for education. For this to happen 'transpositive work' needs to be carried out so that 'something that was not made for school changes into something that may be reconstructed inside school'. (Bosch & Gascón, 2006, p. 53)

This process begins away from school in the choice of which bodies of knowledge have to be transmitted. In England, as in many countries, the choice has been made that physics is to be transmitted to all but that the closely related field of engineering will largely be absent from school. Bosch and Gascón (2006) argue that what follows is creative, not just transferring, adapting or simplifying, as the different elements of the knowledge are deconstructed and rebuilt to make them 'teachable.' This creative work is done by a number of agents including politicians, scholars and members of the teaching system, particularly teachers. Teaching is not possible without this transposition but schools can in consequence lose the 'rationale for the knowledge to be taught' and the 'questions which motivated the creation of the knowledge' (Bosch & Gascón, 2006), resulting in the teaching of knowledge without the questions which lay behind its creation.

The difference between the original and the pedagogic discourse is recognised by Watson (2008) when she acknowledges that however much one might want students to undertake activities in school which are 'authentic', school mathematics is not the same as the broader discipline of mathematics, which she takes to mean the advance of mathematical knowledge 'contributing to the conventional canon of pure or applied mathematics' (p. 3).

> School mathematics is not, and perhaps never can be, a subset of the recognised discipline of mathematics, because it has different warrants, authorities, forms of reasoning, core activities, purposes and unifying concepts, and necessarily truncates mathematical activity in ways that are different from those of the discipline. (Watson, 2008, p. 3)

The same could be argued for the school sciences. This is in part because of the way in which specialist expert knowledge is communicated, requiring translation to be accessible to those outside the small and specialised field of knowledge producers, as Singh explains:

> Specialist expert knowledge is encoded in highly complex symbolic forms and must be decoded or translated (pedagogised) in order to be accessible to those outside the specialist domains. At the same time, knowledge producers do not have the time or resources to convert or translate new knowledge into a form accessible to non-specialist consumers. Thus, the pedagogising of knowledge is increasingly undertaken within agencies of recontextualisation. (Singh, 2002, p. 575)

Singh further argues that those who are undertaking the work of pedagogising knowledge have the power to decide what knowledge is chosen, in other words what the school subject looks like, what it contains and who it is aimed at. Fensham argues that inevitably the science education policy and curriculum which result 'value some groups in society over others' (2009, p. 1076). With the mathematics curriculum there are additional pressures to both be true to the subject itself as a 'major intellectual discipline' and to 'provide the under-pinning language for the rest of science and engineering and, increasingly, other disciplines' (Smith, 2004, p. 2).

Bernstein (2000) distinguishes between *official* recontextualizing fields which are created and dominated by the state and its selected agents and *pedagogic* recontextualizing fields in schools and colleges, university education departments, journals and research foundations. When the state wishes to weaken the influence of schools over the construction of pedagogic discourse then it strengthens the official recontextualising field. This process has been taking place in England with the introduction of the National Curriculum and its subsequent revisions.

4.2.2 Government policy making, networks and interest groups

Recontextualisation or didactic transposition does not happen in a vacuum, although the conditions under which it takes place are not always clear (Bosch & Gascón, 2006). Various interest groups, each with their own particular bias and interests, seek to influence the content and construction of the curriculum. Bernstein argued that:

> Curricula reform emerges out of a struggle between different groups to make their bias (and focus) state policy and practice. (2000, p. 65)

Ball (1990), in his study of the Education Reform Act and the writing of the first national curriculum, notes that educational curricula are always a compromise between different interest groups. These groups are active in the policy arena and each try to impose their own ideology on the transformation of academic disciplines and the construction of school curricula. The ‘outcome of these compromises *are* different at different historical moments’ (p. 214, emphasis in original).

Ball (1990) suggests that the National Curriculum arose out of concerns, expressed by both right and left wing politicians through the 1960s-1980s, that there was a problem, or even a crisis with, particularly state, education in England. He identified three substantive themes in the discourse, predominantly from political speeches and government documentation, each of which involves criticism of comprehensive and progressive education. The first is that ‘academic standards are in decline, particularly standards of literacy and numeracy’ (Ball, 1990 p. 25). This has remained a constant refrain of education ministers to this day and, as it was then, is linked to concerns about economic competitiveness, with the prevailing political ideology being that education must serve the economy (Hill, 2013). Apple, in a paper discussing the purpose of national curricula, identifies a similar focus on industry and the economy in education in the US, identifying ‘growing pressure to make the perceived needs of business and industry into the primary goals of the school’ (1993, p. 4) and that a national curriculum was crucial to a government wanting to be seen to be ‘doing something about raising standards’ (*ibid*., p. 7). The second theme is that of ‘dangerous, politically motivated teachers preaching revolution, socialism, egalitarianism, feminism and sexual deviation’ (Ball, 1990, p. 25). This might lead, for example, to teachers bringing aspects of working-class culture into the school curriculum which was regarded as ‘massively subversive’ (p. 25) by the government. Apple argues that the ‘national curriculum is a mechanism for the political control of knowledge’ (1993, p. 9). In other words, it allows the government to decide what is taught in school rather than leaving that decision to teachers who might otherwise make curricula choices of which the government would not approve. The third theme was that of indiscipline, with comprehensive schooling again identified with a fall in standards, this time in behaviour. This discourse coincided with the change from a division of pupils into separate schools at the age of 11 based on an examination to comprehensive schools for all.

The curriculum and disputes about what would constitute a valid curriculum were central in these concerns. Material that was ‘relevant’ to the student was believed to be taking the place of the harder subjects. The assumption was that new studies and subject matter were necessarily political and biased whereas the traditional subjects were ‘unquestionably neutral and objective’ (Ball, 1990, p. 48). In all the discussions, the models for good practice were the grammar and independent schools as they were perceived to embody traditional moral and cultural values and educational standards (Ball, 1990). Apple (1993) argues that such a focus on the culture of some in society, necessarily to the exclusion of the culture of others, is a common feature of a national curriculum.

> For most of its proponents, a common curriculum must basically transmit both the 'common culture' and the high culture that has grown out of it. Anything else will result in incoherence, no culture, merely a 'void'. Thus, a national culture is defined in exclusive, nostalgic, and frequently racist terms. (Apple, 1993, p. 9)

The strong subject basis to the national curriculum in England has contributed to reinforcing the boundaries around each subject. There were, however, aspects to the first national curriculum, such as practical work and investigations, in both the science and mathematics curricula which stressed 'the need for skills and concepts to be applied across subject boundaries.' (Ball, 1990, p. 136). However, from research in schools in the early 1990s, shortly after the introduction of the national curriculum, Whitty, Rowe and Aggleton (1994) concluded that the nature of the curriculum makes it harder to have cross-curricular themes, as subjects rather than themes are strongly foregrounded by teachers. Thus decisions taken about the curriculum at national level, such as its strong subject basis, have impacts on practice in schools.

The inclusion and exclusion of particular subjects was an issue then (Ball, 1990) and continues to be so over 25 years later. The nature and conception of those subjects is also disputed. What counts as mathematics or science was 'the basis of competition between groups and interests working in and around the field of education' (Ball, 1990, p. 134) and is Bernstein's 'gap in which ideology can play' (2000, p.32). Indeed, Apple argues that 'the very fact of a national curriculum encourages […] intense public debate about whose knowledge is declared official' (1993, p. 11).

4.2.2.1 Contesting the national curriculum for science

In science, debates about the nature and emphasis of the subject continue, as evidenced in the very different visions of science which are presented in the three most recent versions of the secondary science national curriculum: 2004 (DfE and QCA, 2004), 2006 (QCA, 2006) and 2015 (DfE, 2015).

The influential *Beyond 2000* report (Millar & Osborne, 1998) identified three distinct aims for science education: enhancing student interest in science by promoting wonder and curiosity; supporting the development of 'scientific literacy' for all students; and the preparation for further scientific study. The bulk of the report focused on improving scientific literacy. These aims can be identified to a greater or lesser extent in all the national curricula which followed.

In the 2004 science national curriculum, Ryder and Banner (2011) identified the key aim for the curriculum as being: ‘so that more students will be encouraged to study more science’ (DfE and QCA, 2004, quoted in Ryder and Banner, 2011, p. 716), written prominently on the inside front cover. Ryder and Banner demonstrate that, while the curriculum recognised a variety of aims, the most prominent was that of increasing the numbers of students studying science in post-compulsory education. They argue that while enhancing interest and improving scientific literacy are aims for all students, providing the start of a scientific career is clearly only an aim for a few; these multiple aims create tensions in what is to be prioritised in the science curriculum.

In contrast, in the 2006 curriculum (QCA, 2006) Ryder and Banner argue that the ‘demands of subject maintenance are less visible’ (2011, p. 720). They suggest that traditionally the stakeholders who have argued for the prominence and identity of the separate sciences are professional scientists, who were not central players in the development activities which led to this particular curriculum. They identify this reduction in visibility with a shift in ownership of the science curriculum away from professional scientists, with the prominent stakeholders for the 2006 curriculum being university-based science education researchers. This shift is probably due to the influence of the Beyond 2000 report (Millar & Osborne, 1998).

In England, the interests of the professional scientists as stakeholders in the curriculum are usually channelled through the learned societies. Working together as SCORE, the learned societies had considerable impact on the development of the 2015 curriculum, with multiple drafts being commented on by education departments of each society (pers. comm.). Some of the comments on these drafts are available publically on the SCORE website (SCORE, 2014). In the 2015 curriculum the first aim of the curriculum is stated as: ‘enabling students to develop scientific knowledge and conceptual understanding through the specific disciplines of biology, chemistry and physics’ (DfE, 2015, p. 5). This aim, together with the much greater specificity of subject content compared to the 2006 version, suggests that the ownership of the science curriculum has shifted once again towards the professional scientists with the needs of students who might be expected to continue with their study post-16 valued over those of science for all and scientific literacy.

These three very different curricula thus demonstrate, as Ball (1990) argued, that the outcome of the compromises between groups interested in the curriculum are different at different moments in time. The curriculum has to be enacted in schools who are impacted, even though they may not realise it, by outcomes of tensions and struggles in policy development.

4.2.2.2 Networks and policy making

Ball (2007) demonstrates that more recently there are new participants in the arena of education policy with education businesses, other social actors with various relationships to business and new philanthropists 'inside' policy. He identifies and separates two types of groupings: partnerships, which are fairly stable with defined structures and protocols, and networks. Networks are contested and subject to several different interpretations (Ball & Junemann, 2012). The term 'networks' will be used here to describe several interdependent actors from a number of different organisations involved in defining and delivering a policy agenda. These networks may be harmonious but they can be large and conflict-ridden with members only loosely connected. This type of policy making is, by its nature, rather opaque. It also requires collaboration across discipline and professional boundaries. Many authors have written about collaboration (for example, Perkins, 2003, Carlile, 2004, Edwards, 2011) in a very wide range of settings, but they virtually all agree that collaboration across disciplinary or professional boundaries is not straightforward.

As a result of the opacity of networks it can be difficult to know who has the real power within them, or where the most significant connections lie. Ball and Junemann argue that 'important aspects of network relations consist of informal social exchanges […] that go on behind the scenes' and that it is only possible to access 'glimpses of influence, pale imitations of the real social interactions […] that ties people together in relationships and gets things done' (p.80). It is thus difficult to unpick who has influence within a network.

Ball and Junemann (2012) further argue that the UK government is increasingly using policy networks to bring new solutions to difficult problems by bringing together traditional government agencies and public bodies with private, voluntary and philanthropic organisations which have an interest in the issue at hand. One example is persistently low numbers of students choosing to study STEM subjects at university and, prior to that, in post-compulsory schooling, identified as problematic in the Roberts' Review (2002). Networks are particularly expedient when the problems identified transcend organisational boundaries. As STEM, however it is defined, by its very nature transcends the majority of organisations, a network may be the most obvious means of making policy. The UK government developed a STEM policy network to advise them, with the formal network known as the *STEM High Level Strategy Group*. As with all types of policy making, there are benefits and disadvantages to networks. Involvement can help to establish relationships with the state for non-state actors, and provide a wide variety of opportunities to engage in policy conversations resulting from access to the decision-making sites of government. It can lead to the receipt of awards, honours and appointments (Ball & Junemann, 2012). One potential drawback is that, as Millar (2014) identifies, many influential bodies in England have perceived interests which lead them to promote policies which prioritise science education for the 20 percent who go on to study more advanced academic science and resist any changes designed to address the needs of the vast majority whose science education ends at age 16.

The rationale for the UK government's focus on STEM was economic (Wong, Dillon, & King, 2016). Increasingly, ideology which is expressed in policy making is related predominantly to economic competitiveness, as Ball argues:

> Within policy, education is now regarded primarily from an economic point of view. The social and economic purposes of education have been collapsed into a single, over-riding emphasis on policy making for economic competitiveness and an increasing neglect or side-lining (other than in rhetoric) of the social purposes of education. (2013, p. 14)

This economic rationale for education is not without its critics. For example, Pring *et al*. (2009) argue that the economic rationale is narrowly conceived and impoverishing, calling for a broader vision of education with a 'profound respect for the whole person […] irrespective of ability or ethnic or social background' (p. 208). That respect would be reflected in curriculum language which expresses the 'essentially moral purpose of education – helping young people to develop their distinctively human qualities' (*ibid.,* p. 208).

4.2.3 Summary

In summary, any academic discipline has to be re-contextualised or transformed into a pedagogic discourse. Between the original discipline and the pedagogic discourse there is a gap where ideology can come into play, as transformation does not take place in an ideological vacuum. Indeed, even which subjects are to be included in school curricula and the need for a national curriculum itself is ideological. The question then, perhaps, is whose ideology? As network policy making has become more prevalent and individuals, organisations and partnerships within these networks become more influential, it can be difficult to determine whose ideology is at play, with the parties involved perhaps not having an equal interest in the education of all students. Increasingly the ideology which is at the forefront of government policy making is economic competitiveness, with the requirement of education to supply the needs of the economy taking precedence over any social purposes it may serve. This, as may be expected, is not uncontested, with authors including Pring *et al*. (2009) arguing that there should be a broader moral purpose to education, with it explicitly existing for the benefit of all students.

4.3 Transfer

4.3.1 A contested idea

In the educational literature the use or application in one context of knowledge learned in another is known as *transfer.* It is a contested idea with authors expressing a wide range of views as to what it is, whether it exists and if and how it can be promoted by education. According to Royer, Mestre and Dufresne (2005), 'The question of how transfer works, and how transfer can be facilitated is a vitally important educational issue' (2005, p. vii). Osborne (2011, 2014) suggests that many science teachers hold a 'vaccination' view of mathematics in science, feeling that it is not their responsibility to educate students in the mathematics that they require in science and that if students have not been appropriately vaccinated there is little that as science teachers they could or should do about it. Similarly, Goldsworthy *et al*. (1999) found that, although science teachers recognised that students struggled with graphing, they did little to help them improve their skills in graph construction and interpretation; Scott (2012) argues that the mathematics classroom is the place where students' difficulties with using mathematics in science should be solved. Likewise, in research carried out with Dutch teachers, Turşucu, Spandaw, Flipse, & de Vries (2017) found that the majority thought that the so-called transfer problem, students finding it difficult to use mathematics within science, should be solved by more intensive practice in the mathematics classroom; in other words they held the 'vaccination' view identified by Osborne. Assuming that Osborne is correct, and the vaccination view is dominant in England, suggests that a naïve view of transfer predominates among science teachers, ignoring the considerable body of research that demonstrates that students find using mathematics in other contexts very difficult (for example: Dodd & Bone, 1995; Goldsworthy *et al*., 1999; Frade *et al*., 2009; Redish & Kuo, 2015.)

Transfer may be a useful concept, but it is not an idea without its difficulties. Frade *et al*. (2009) note the 'controversial notion of transfer [and] the clear diversity of views of transfer in the mathematics education literature' (p. 14), where it is discussed far more extensively than in the science education literature. Transfer has been explored by authors from a wide range of disciplinary backgrounds including social anthropology (for example Lave, 1988), mathematics (for example Boaler, 2002), psychology (for example Barnett and Ceci, 2002), language learning (for example Larsen-Freeman, 2013) and, to a more limited extent, science (for example Rebello *et al*., 2005). As a result of the range of disciplinary backgrounds, transfer has been conceptualised through a variety of different theoretical lenses, giving rise to a range of perspectives. Perhaps as a consequence there is little agreement among scholars about the nature of transfer, the extent to which it occurs, and its underlying mechanisms.

Boaler (2002) suggests that one's understanding of transfer is related to the theory of learning one subscribes to. She argues that both behaviourist and constructivist theories of learning, while very different, represent 'knowledge as a characteristic of people that may be developed and then used in different situations' (p. 42). A behaviourist view, for example, would lead to plenty of practice of mathematical methods, with the underlying assumption being that knowledge which has been clearly communicated and received would be available for future use, including in new contexts (Boaler, 2002). Schwartz, Bransford and Sears argue that constructivism by its very nature involves transfer as 'whenever we assert that new learning builds on previous learning, we are assuming that some sort of transfer is involved' (2005, p. 11) and 'research on preconceptions involves paying attention to what people transfer in as it will profoundly affect what they learn' (p.9).

In contrast, Lave and Wenger (1991) argue that learning is situated, occurring in a context and a culture, and therefore students do not bring parcels of knowledge from mathematics with them into other contexts, including science lessons. They propose that learners learn within a 'community of practice' with social interaction a critical aspect of situated learning. Boaler (2000) explains that the situated learning perspective recognises that people use knowledge differently in different situations:

> This perspective [situated learning] emerged from a recognition that people use knowledge differently in different situations and that knowledge, rather than being a stable, individual entity, is co-constructed by individuals and by other people with

> whom they are interacting in conjunction with aspects of the situation in which they are working. (2000, p. 42)

If, however, science educators hold the view that knowledge can be developed in one situation and then used in another, in other words that it is a stable individual entity, it would explain why they expect that transfer of knowledge from mathematics to science will cause minimal difficulty for students. The assumption that transfer will be straightforward will tend to lead to deficit views of both students and mathematics teachers if, or rather when, the expected transfer is not seen.

4.3.2 A deficit view of transfer

Some authors argue that transfer *should* happen and question why it does not, even suggesting students show an active resistance to transferring knowledge. Dodd and Bone mark ‘the frequent inability or reluctance of pupils to transfer knowledge and understanding from the mathematics classroom to the science laboratory’ (1995, p. 103). Lerman (1999) identifies the problem of transfer as what happens when people perform differently on what, to a mathematician, is the same task in different contexts. Larsen-Freeman suggests that it is a common problem that students ‘fail to transfer their learning’ where, although they appear to have learned something in one context, they cannot activate it in another (2013, p. 107). These authors all appear to hold a deficit view when comparing how students perform compared to how it might be hoped they would perform. Lobato (2012) suggests the deficit view holds sway as teachers do not notice when students *do* transfer their learning and, consequently, transfer is more often noted when it does not happen than when it does.

Lack of apparent transfer can also be viewed as a deficit on the part of those teaching in the original site of learning; in the case of mathematics and science this is often viewed as a deficit in mathematics teaching. For example, in a paper about students’ difficulties with mole calculations, Scott concludes that an:

> algorithmic approach to mathematics teaching hinders problem solving ability in other subjects, most notably in the sciences. This is a […] challenging issue to solve in which the action to be taken would be in the mathematics classroom rather than the science classroom. An improved communication between science departments and mathematics departments will be important in solving this problem. (2012, p. 336)

In other words, Scott holds that it is not the responsibility of science teachers to help students to use mathematics within science. Instead, he asserts that it is in the mathematics classroom that the 'action' will take place, with the apparent expectation that transfer from mathematics to science will be unproblematic. He clearly holds a deficit view of mathematics teaching, blaming it for students' difficulties problem solving in science.

It has been suggested by some researchers that if students originally learn something in sufficient depth then they will be able to transfer it, with shallow learning leaving them unable to do so. In reviewing a number of studies, Barnett and Ceci suggest that:

> Children transferred most successfully when they understood events at a causal level rather than merely learned to replicate particular behaviors. That is, they transferred when they developed a deep, rather than surface, understanding. (2002, p. 616)

There is undoubtedly some truth in this assertion, in that students will be unlikely to be able to use elsewhere something that they did not understand in the first place. However, this line of thinking is somewhat problematic as it leads some authors, such as Scott (2012), to suggest that students struggle to use mathematics in science lessons as they do not understand the material sufficiently well to transfer it to a novel context. Suggesting that it is the inadequacy of the initial learning which is at fault when students find using the knowledge in another context challenging additionally ignores research which shows that understanding of the context being transferred *to* is also important:

> Knowledge about the area to which the principle is to *be* transferred is *also* key to successful transfer. Children cannot apply learned causal schemas to a subject about which they know nothing. (Barnett & Ceci, 2002, p. 616, emphasis added)

Another complication is noted by Porkess; that transfer is not just a problem for students who find mathematics difficult:

> There are students who are successful in mathematics who are nonetheless unable to put the techniques they have learnt to use in other subjects. (2013, p. 36)

There is thus more to students' difficulties with transfer than simply not understanding what was originally taught.

4.3.3 Problems with transfer research

Larsen-Freeman (2013) has highlighted that there are significant problems with much research into transfer, particularly problematizing that which has been undertaken in laboratories rather than in natural learning environments. Transfer is often measured in sequestered problem solving (SPS) contexts, so-called as the participants are sequestered in order to protect them from contaminating information. Consequently, participants complete tasks which are isolated from additional knowledge resources that would be typically available to them in non-laboratory settings.

Schwartz, Bransford and Sears argue that many of the examples given for lack of transfer make people 'look dumb' (2005, p. 6) as the definition of transfer is too narrow. One of the most widely cited examples for learning being situated in context and not transferrable is Lave's (1988) classic study of shoppers. She showed that educated adults could compare prices in supermarkets but not solve isomorphic school-type problems of a similar nature and concluded as a result that their learning had not transferred. She concluded that learning is therefore situated in a particular context and not generalizable beyond it. Adey (1997) challenged her conclusions, arguing that in a shopping situation estimates and best guesses are appropriate whereas in a school situation an estimate or best guess would be marked incorrect unless it happened to be right. In other words, the problems are not isomorphic as the responses which are acceptable are not the same. He also pointed out that just because 'real-life' mathematical ability does not appear to transfer to school situations the converse does not necessarily follow.

In exploring transfer between mathematics and science, isomorphic problem solving questions are often used (for example Bassok & Holyoak, 1989; Scott, 2012; Zhang, Orrill, & Campbell, 2015). As discussed in Chapter 3, there are significant difficulties in ensuring that problems genuinely are isomorphic. This contributes to the difficulties in drawing valid conclusions about transfer from such experiments.

4.3.4 Preparation for future learning

Part of the difficulty with measuring transfer lies in how it is conceptualised. When transfer is considered as preparation for future learning (PFL) rather than direct application of knowledge it is measured as occurring more widely. Bransford and Schwartz (1999) report that studies which ask how experience with one set of skills affects people's ability to learn a second set of related skills found greater evidence of transfer on the second day than on the first. They argue that 'one-shot sequestered problem solving tests of transfer are often too weak to detect effects such as these' (1999, p. 69). In a later widely cited chapter strengthening the case for this view, Schwartz, Bransford and Sears (2005) make the distinction between three different types of knowing: replicative (knowing that, in other words recall of facts); applicative (knowing how, in other words using previously acquired knowledge to solve new, transfer, problems); and interpretive (knowing with). They argue that traditional answers to the 'what gets transferred' question are usually restricted to replicative and applicative knowing. When interpretive knowing is assessed it is possible to see positive benefits to schooling (i.e., transfer) in the thinking of most people. They argue that:

> For many new situations, people do not have sufficient memories, schemas or procedures to solve a problem, but they do have interpretations that shape how they begin to make sense of the situation. (Schwartz, Bransford, & Sears, 2005, p. 9)

They define interpretive knowing as in large part about what a person notices about a new situation and how they frame problems which, they argue, have major impacts on subsequent thinking and cognitive processing. They suggest that people are often unable to articulate explicitly the ideas that changed their interpretations, but that they are still knowing with (interpretive knowing), even if they cannot recall specific facts (knowing that) or procedures (knowing how). There is, they argue, a significant difference in asking whether students can directly apply old knowledge to solve new instances of problems or asking whether students have been prepared to learn to solve novel problems. Interpretive knowing, they suggest, can be viewed as 'seeds for new learning' and can be activated even when there is limited recall of specific facts (replicative knowing) or procedures (applicative knowing). When viewed from the perspective of preparation for future learning, transfer is observed as occurring more frequently than in sequestered problem solving experiments.

4.3.5 Negative transfer

Negative transfer occurs when learning in one context impacts negatively on performance in another (Perkins & Salomon, 1992). The term is rare in both the science and mathematics education literature, where the focus is overwhelmingly on positive transfer, although the phenomenon of misconceptions, widely discussed in science education, could be interpreted as persistent or undesirable transfer, in other words negative transfer. Negative transfer is a concern in language learning where the difficulties of learning multiple languages are discussed in these terms (Larsen-Freeman, 2013).

Fisch, Kirkorian and Anderson (2005) suggest that negative transfer occurs when students perceive similarity of surface structures to problems and apply previously learnt problem-solving schemas, not appreciating that the deep structure of the problem is different. Schwartz, Bransford, & Sears (2005) evaluate the results of an experiment into transfer and note that there were strong influences of previously acquired knowledge, but that they all looked like instances of negative transfer rather than positive transfer. In the experiment, groups of college students and fifth grade students (10-11 years old) were given the problem of developing a state-wide recovery plan for eagles. In the initial test they were asked to directly apply any previous knowledge to solve the problem; all the plans were completely unworkable. In the second test they were asked to generate questions they would like to have answered to learn about eagle recovery plans. The second test showed that both groups knew more than nothing about the topic, with the college students producing more sophisticated questions. The first test focused on replicative and applicative knowing but the second test focused on interpretive knowing; by assessing interpretive knowing the transfer picture was far more encouraging. Schwartz *et al*. found that many instances of negative transfer were lightly held conjectures which people initially applied cautiously but were willing to let go, leaving an overall positive impact on problem solving. The problem with this research is that it is very difficult to argue that schooling and learning (and thus applicative knowing) led to the differences, rather than greater maturity – or any of the other differences between a 10 year old and an 18 year old.

4.3.6 Transferring in and out

Schwartz, Bransford and Sears (2005) suggest that there is a correlation between how frequently researchers find transfer and whether they are looking at transfer *in* to a learning situation or transfer *out* for subsequent problem solving and future learning.

There is a key difference in the focus on transfer between the mathematics and science education literature. In mathematics education the focus is predominantly on students being able to use what they have learnt in mathematics in other disciplines and in the wider world. For example, Lerman (1999) argues that mathematics teachers want children to be able to use their mathematics in different life situations which would be described, at least by mathematicians, as mathematical. He suggests this is a widely held aim for mathematics teaching but that it is very difficult to achieve. In science education the primary focus is rather on students using what they have learnt elsewhere, particularly in mathematics, within science. Thus the focus for mathematics education is on transfer *out* of the site of learning into other contexts whereas the focus for science education is on transfer *into* science from learning elsewhere. (One notable exception to this is Adey and Shayer's 1993 study into the effects of the CASE (Cognitive Acceleration in Science Education) programme on achivement in mathematics and English as well as in science).

If Osborne's (2014) view is correct, i.e., science teachers expect mathematics education to act as a vaccination such that they do not have to teach any mathematics, science teachers' expectations are of replicative and applicative thinking. In other words, their expectation is that students will 'know that' and 'know how' – and be able to use this knowing to solve problems without much additional teaching or assistance. This, as explained above, is likely to lead to frustration, and a deficit view of both students and mathematics education. If instead students' prior mathematics study is seen as preparation for future learning then science teachers might expect that prior study of a topic in mathematics would make it easier for students to learn in science, although – and this is critical – they would still need additional teaching in that topic in science. An example of this might be that the prior study of proportional reasoning could make it easier to learn about moles, mole ratios and concentration, all of which depend on proportional reasoning. Crucially, teaching about the specific science and the application of proportional reasoning to that science would still be required.

4.3.7 Teaching and transfer

Different models and taxonomies of transfer have been suggested, for example by Barnett and Ceci (2002) and Royer, Mestre, and Dufresne (2005). These and other authors have made a distinction between near and far transfer. Near transfer takes place between two similar contexts and, for Barnett and Ceci, nearness in time. Far transfer is across very different contexts and is thought to occur via analogic reasoning. Far transfer is difficult as students often do not see the connections, or analogies, between the different contexts (Larsen-Freeman, 2013). As near transfer is easier it is perhaps not surprising that a number of authors (for example Barnett and Ceci, 2002, and Larsen-Freeman, 2013) suggest that the most successful transfer is achieved when the retrieval conditions are closely related to the conditions of initial learning.

Rebello *et al*. argue that 'transfer is more likely if students are given the opportunities to reconstruct their learning in the transfer context in the same way as they did in the learning context' (2005, p. 220). In other words, if students are going to use mathematics in science they need to reconstruct their mathematics learning in the same way in science as they did in the original mathematics lesson. This will require the science teacher to have knowledge of how students were taught in mathematics.

Although she uses different language, Larsen-Freeman (2013) also rejects the idea that students passively carry knowledge over from one context to another. She suggests that students need to transform their knowledge. For her 'the transformation is partly due to the learner's interacting with a different and changing context and partly due to internal reorganization' on the part of the learner (2013, p. 119). This transformation could be seen as another way of describing interpretive, knowing with, thinking, and preparation for future learning. In either case, the focus is on students doing something with their knowledge from prior learning – that 'something' being either new learning or transforming – rather than simply considering learning as a parcel which can be moved from one site to another and opened unchanged in the new location. Other authors have concluded that transfer is not something which an individual does in isolation, but that social and environmental factors are also influential, such that transfer is mediated by teachers, peers and other social influences (Royer *et al*., 2005; Frade *et al*., 2009).

Theories of communities of practice were used by Frade *et al*. (2009) where the aim of their intervention was to set up a mathematics-science community of practice which would enable students to use their knowledge across the two subjects. Although coming from a different perspective, the outworking of their community of practice is similar to the suggestions by Barnett and Ceci (2002) that the greater the similarity between the contexts, the greater the chances of transfer taking place, and by Rebello *et al*. (2005) who argue that students need to reconstruct their learning in the same way as they originally learnt it.

Seeing links across subjects may even be inhibited if students understand and appreciate the strength of the classification of subjects. This phenomenon does not seem to have been investigated with respect to the use of mathematics, but has been documented in the use of oral work:

> Pupils who had learnt successfully to differentiate subjects according to whether or not, and in what ways, oral work was legitimate were actually inhibited from making thematic links across subjects by their very success in recognizing the distinctions between the different subject discourses. (Whitty, Rowe, & Aggleton, 1994, p. 173)

In other words, if students understand how subjects use oral work differently then they will be less likely to use their knowledge across different subject discourses. This might perhaps begin to explain the observations of Porkess (2013) that some students who are successful in mathematics struggle to use their knowledge in other contexts. If they recognise the distinctions in how mathematics is used across subjects it may inhibit them from making thematic links across disciplines and using their mathematics within science effectively.

4.3.8 Summary

In summary, transfer has been conceptualised and described in different ways but is generally considered the use in one context of knowledge learned in another. The so-called problem of transfer has been approached from many different theoretical perspectives by researchers from many different disciplinary backgrounds. Transfer is not viewed as straightforward by any of the authors who have seriously investigated it, if it is even considered to take place at all. Even so, some authors and educators still expect transfer of learning to be uncomplicated and the 'vaccination' view of mathematics teaching described by Osborne (2011, 2014) is widely held. Inevitably, this leads to a deficit view of students who find using mathematics within science hard or nearly impossible. It can also lead to a deficit view of mathematics teaching, where students' struggles to use mathematics within science is ascribed to inadequate prior teaching and learning in mathematics lessons.

Authors have approached the question of how to help students to successfully use their prior learning from a number of different perspectives. The range of standpoints and conclusions suggest again that it is considered a demanding activity. Larsen-Freeman (2013) suggests that students need to transform their learning in the new context and require assistance in doing so; Rebello *et al*. (2005) suggest that students need to reconstruct their learning in a new context and that similarity to the original context will help. This is akin to conclusions reached by Barnett and Ceci (2002), along with authors who take a situated learning perspective, that students will find transfer more straightforward the more similarities there are between the contexts. Schwartz *et al.* (2005) suggest that transfer should rather be considered as preparation for future learning (PFL) and that PFL should be looked for rather than the ability to recall facts and procedures. From all these perspectives, students would still require teaching of previously learned mathematics within science, but they should learn faster than if they did not have that prior learning.

The difficulties students, and teachers, have in transferring their knowledge from one subject to another may also be part of the answer to why it is so difficult for strongly classified mathematics and science curricula to be mutually supportive.

4.4 Identity and beliefs

4.4.1 Identity

There are a multiplicity of meanings and cognate terms ascribed to the idea of 'identity' (Lee Y.-J. , 2011). Gee defines identity as 'the 'kind of person' one is recognized as 'being' in a given context (2000-1, p. 99). He acknowledges that identity can change even from moment to moment in an interaction and that identity can change from context to context, that it can be ambiguous or unstable. People have multiple identities connected not to their internal states but to their performances in society, although each has a 'core identity' that holds more uniformly across contexts. Carlone and Johnson argue that one cannot claim an identity all by one's self; the participation and acquiescence of others is required as 'one makes visible to (performs for) others one's competence in relevant practices, and, in response, others recognize one's performance as credible' (2007, p. 1190). They argue for three dimensions of identity: competence, performance and recognition.

The concept of identity is a useful 'pivot between the social and the individual, so that each can be talked about in terms of the other' (Wenger, 1998, p. 145). Thus identity can provide a useful way of pivoting or linking between interactions as subjects or departments and as individual teachers. I showed earlier in this chapter that Bernstein (2000) argues that category identity can be lost when insulation between those categories is broken. Indeed, Newman argues that borders 'will always demarcate the parameters within which identities are conceived, perceived, perpetuated and reshaped' (2003, p. 15). Ball (1987) and Siskin (1994) show that many secondary teachers identify with their subjects and that their professional, and even personal, identity is wrapped up in their subject identity. Thus, breaking subject barriers challenges teachers' personal identities not just department identities; if there is no 'science department' then are they truly a 'science teacher'? Ball (1987) demonstrates that innovation can undermine established identities, both institutional, for example as departments, and personal, which helps to explain why collaboration may be resisted by some teachers.

4.4.2 Identity and learning

For Wenger 'identity exists [...] in the constant work of negotiating the self' (1998, p. 151). He argues that learning impacts identity because it is transformational:

> Because learning transforms who we are and what we can do it is an experience of identity. It is not just an accumulation of skills and information, but a process of becoming, to become a certain person or, conversely, to avoid becoming a certain person. (Wenger, 1998, p. 215)

The transformation comes about partly as it can change the ability to participate in the world, although such participation is not automatic (Wenger 1998). Boaler and Greeno (2000) argue that the way in which mathematics is taught can affect the likelihood of learning changing the ability to participate in the world. In mathematics classrooms both the type of mathematical activity and the way that mathematics teachers and students interact can vary hugely (Cobb, 2004). Boaler and Greeno argue that traditional pedagogies and procedural views of mathematics, when combined, result in students needing 'to surrender agency and thought in order to follow pre-determined routines' (2000, p. 171). Although capable of doing mathematics, many students reject these practices as they 'run counter to their developing identification as responsible, thinking agents' (*ibid*.). Boaler later links this development of identity to transfer, arguing that when students were able to transfer mathematics it was:

> partly because of their knowledge, partly because of the practices in which they engaged and partly because they had developed an active and productive relationship with mathematics. (2002, p. 47)

She proposes 'developing a productive relationship with the discipline of mathematics' as providing the link between knowledge, practice and identity. Students who have developed such a relationship are, as a result, able to appropriate their knowledge by finding a way to relate to it. Other students may have 'mastery' of mathematics, but without this 'active and productive relationship with mathematics' they are unable to use it outside the mathematics classroom. Boaler (2002) found that many students talked about their dislike of mathematics not because of the cognitive demand of the subject, but because the practices of the mathematics classroom left them no room for their own interpretation or agency. Such practices precluded them from developing a productive relationship, even though they might be able to succeed within the mathematics classroom. This may help to explain Porkess's observation (2013) that students can succeed in mathematics but be unable to use it elsewhere. Other authors have written about the idea of a 'science identity', although as a concept it is 'slippery and difficult to operationalize in a way that provides solid methodological and analytic direction' (Carlone & Johnson, 2007, p. 1189).

The challenge for the science teacher is to allow access to the mathematical aspects of the science curriculum even for those who, for whatever reason, have not developed a 'productive relationship with mathematics' (Boaler, 2002, p. 47).

4.4.2 Teacher beliefs and responses to change

It is widely recognised that teachers' beliefs play an important role in their pedagogical decision making, both prior to and during a lesson (Wallace, 2014). It has been claimed by many researchers that 'beliefs are the best indicators of the decisions that individuals make throughout their lives' (Pajares, 1992, p. 307). This is in spite of a lack of consensus over the definition of beliefs, described by Pajares (1992) as a 'messy construct'. Bryan (2012) suggests that beliefs are based on evaluation and judgement, contrasted with knowledge which is based on objective fact, but accepts that this is an artificial distinction. She further suggests that beliefs do not exist in complete independence of each other, with not all beliefs being equally important to the individual who holds them. Some beliefs are more core than others, with the most central beliefs being the most resistant to change. Beliefs are more influential than knowledge in determining an individual's behaviour.

Glackin (2016) evaluates teacher responses to a professional development programme and argues that beliefs are important for how teachers respond to suggested changes to their practice. Wallace agrees and contends that teachers may 'review and filter new curriculum innovations for those that resonate with [their] core beliefs' (2014, p. 18). She explains that research has found that when interventions are at odds with beliefs, teachers will either refuse to implement them or do so superficially. This could be expected to be the case with closer collaboration between mathematics and science; as with any other intervention it will be unlikely to happen if teachers do not believe it to be valuable.

Espoused beliefs and teacher practice are not always congruent. Part of the reason for the difference can be the context in which the teacher is working; it can be risky for a teacher to assert their beliefs in opposition to what is valued by school management. There can be tensions between a teacher's beliefs and accountability pressures, with school policies often acting to reduce teacher agency (Wallace, 2014).

A concept connected with beliefs is self-efficacy, which refers to the beliefs that a person has in themselves and what they can do with the skills that they possess (Bandura, 1997). Self-efficacy links to belief as it 'affects the extent to which core educational beliefs can be enacted' (Glackin, 2016, p. 4). Efficacy beliefs are the foundation of human agency. Unless people believe that they can produce desired results by their actions, they have little incentive to act or to persevere in the face of difficulties. Self-efficacy can be strengthened in a number of ways but the most important is through mastery experiences, as the experience of success builds belief. Mastery experiences can be 'enactive', doing something successfully, or 'cognitive', which can develop through understanding the theories of a chosen pedagogical strategy (Palmer, 2011). Glackin (2016) suggests that teachers require both enactive and cognitive mastery experiences to change their practice.

Considering collaborative work across mathematics and science departments, teachers might be more likely to change their practice if they have both enactive and cognitive mastery experiences. Such experiences might include positive successes in prior study of mathematics, for example. It is possible that many science teachers will not have developed what Boaler describes as a 'productive relationship with mathematics' (2002, p.47) as they have had negative experiences of learning mathematics. The impact of those negative experiences will have potential implications for how they respond to increasing mathematical demand within the science curriculum as well as conceivably influencing how they respond to calls for collaboration with mathematics colleagues. Other mastery experiences might include understanding and valuing the theories behind the proposed integration. If such theories are absent or unexplained then the opportunities for mastery experiences for the teacher are more limited and there is thus less likelihood of a change in professional practice.

4.5 Theoretical framework

The analyses of the data will be framed by the work of Bernstein, and in particular his last book *Pedagogy, symbolic control and identity* (1996, 2000). In it, he argues that 'A can only be A when it can separate itself from B' (2000, p. 6). He describes what he calls 'punctuations in social space' (*ibid.,* p. 5) which are produced by power relations and act to reinforce the boundaries between entities, which in this study are departments and academic disciplines. Factors which contribute to the isolation of departments have been suggested by Bernstein and identified in practice by Ball (1987) and Siskin (1994) and include language differences, competition for resources, external assessments, physical spaces and teachers identifying with their department. Breaks in the insulation of entities can lead to loss of power for both parties. Bernstein argues that when examining innovations which change the classification or insulation of a subject or department, it is important to consider who is initiating the change, whether they are dominant or dominated, and who is benefitting.

This issue of power brings us to the second theoretical perspective: the importance of the role of policy on educational practice as argued by Ball (1990) and Fensham (2009). Increasingly the ideology at the forefront of policy is that of economic competitiveness, with the requirement of education to supply the needs of the economy taking precedence. Policies interact with and shape the way school practices are perceived, advanced and held accountable. Fensham (2009) suggests that when considering policy it is important to ask whose ideology is prevailing or which stakeholders have been successful in shaping policy, together with asking which groups in society will be advantaged and which disadvantaged by science education practices resulting from those policies.

In examining the data through the lens of Bernstein and Ball, it will be relevant to consider the ways teachers identify with their departments (Siskin, 1994), and how collaboration can threaten that identity by challenging teachers' feelings of competence, their performance in the classroom and their recognition or status. Teacher beliefs about their subject and their practice will help in understanding how they perceive and enact collaboration.

Finally, it will be useful to consider the idea of transfer. Improving transfer between mathematics and science is behind many of the calls for increased collaboration, even if this is not explicitly stated (Honey, Pearson, & Schweingruber, 2014). Transfer between subjects involves cutting across department boundaries and therefore challenges, and is challenged by, those boundaries. Whether transfer is even possible, and under what circumstances, has profound implications for science education given its dependency on mathematics, and as such it raises questions for both policy and practice.

In examining the schools and policy makers data through the lenses of boundary, policy and identity, and in examining the descriptions of transfer, I will be able to move beyond simply describing the relationship between school science and mathematics education in England to a position of theorisation and explanation.

Chapter 5
Methods and methodology

5.1 Methodology

In the sciences, research might involve, among other activities, testing, counting, repeating, replicating and measuring. The research designs are predominantly positivist and employ quantitative strategies. Researching human behaviour, on the other hand, including researching the behaviour of those engaged in teaching or developing policy in the sciences and mathematics, requires an alternative epistemological and ontological framework and thus methodological approach. As a chemical scientist I had been educated within a positivist epistemology and never had any cause to doubt its worth, but while generating appropriate graphs is a very powerful way of finding out about molecular structures, it is perhaps less useful for investigating social structures.

This study aims to develop a better understanding of the relationship between school science and mathematics education, with a particular focus on how this relationship both affects and is affected by education policy and practice in England. It asks:

1. How and to what extent can mathematics and science educators work together?
2. What are the barriers to effective, mutually beneficial, collaborations between mathematics and science teachers?
3. How might these barriers be addressed?

An empirical investigation with experimental data as the source of knowledge was not suitable for this type of enquiry and so a qualitative approach was taken.

> Qualitative researchers stress the socially constructed nature of reality, the intimate relationship between the researcher and what is studied, and the situational constraints that shape inquiry. They seek answers to questions that stress how social experience is created and given meaning (Denzin & Lincoln, 2000, p. 8).

In Chapter 2, I demonstrated the existence of a policy rhetoric which promotes STEM (Science, Technology, Engineering and Mathematics) in many countries, thereby linking mathematics and science. In Chapters 1 and 3, I noted that many authors have called for closer links between mathematics and science but, despite this, few studies have investigated what collaboration between mathematics and science looks like in practice in schools or have examined the development of policy at the interface between mathematics and science education. This study, therefore, concentrates on the perspectives of those who are involved in either developing policy or in cross-department collaboration in schools in order to fill the gap in the literature identified by Osborne (2011, 2014) and others.

This research seeks to understand how relationships between school science and mathematics are created, maintained and explained. Relationships are social situations, and social reality and experience are, for many people, 'messy and contradictory' (Braun & Clarke, 2013, p. 24). Qualitative research can embrace that messiness and consequently 'we can find out things that we might never have imagined; things that would be lost using quantitative methods' (*ibid*.) Consequently, I have adopted an interpretivist approach, as exemplified by Scott and Usher who state that the 'the goal of research becomes that of providing interpretations of human actions and social practices within the context of meaningful, culturally specific arrangements' (2010, p. 29). This study will ask how meaning is constructed and the how interactions between mathematics and science teachers and policy makers are negotiated to try to better understand the relationship between the subjects, through the frames of those interviewed.

This approach is not without its difficulties. As Scott and Usher point out, 'No interpretation can ever be uniquely correct, because that would presuppose that there is *an* interpretation that is authentic' (2010, p. 30, emphasis added). As a consequence there are no algorithms which can be applied or standard methods followed which will lead to the one unique interpretation or definitively ascertain which of conflicting interpretations are correct. Interpretations can thus 'never be objective in a positivist sense' (*ibid*.)

> Since social action is the outcome of knowledgeable and reflexive actors interacting with other knowledgeable and reflexive actors, explanations of social action must always remain indeterminate; in other words, no explanation is ever definitive but always retains a capacity for resisting closure. (Scott & Usher, 2010, p. 31)

There is, thus, no method of producing the definitive answer to the research questions and the research is necessarily subjective. Braun and Clarke explain subjectivity thus:

> We as researchers, bring our own histories, values, assumptions, perspectives, politics and mannerisms to research – and we cannot leave those at the door. (Braun & Clarke, 2013, p. 36)

Qualitative research thus recognises that the results may be different were the work carried out by a different person. Braun and Clarke argue that in order to use subjectivity effectively it is important to be reflexive, in other words to critically reflect on the knowledge produced and our role personally in producing that knowledge.

5.1.2 The personal dimension

It is important to acknowledge why I have an interest in trying to understand the relationship between school science and mathematics and what previous experience I have had which has led me to conclude that this is a topic that warrants investigation.

Scott and Usher (2010) call these previous experiences 'pre-understandings' and argue that acknowledging them and being aware of them is important in creating new knowledge. They argue that:

> In the process of interpretation and understanding [pre-understandings] are put at risk, tested and modified through the encounter with what one is trying to understand [...] Rather than suspending them, we should use them as the essential starting point for acquiring knowledge […] however […] they need to be left open to modification in the course of the research. (2010, p. 32)

Rubin and Rubin argue that neutrality – the complete absence of prejudice or bias – is impossible to attain and should not be a goal in qualitative research as it does not 'equip the researcher with enough empathy to elicit personal stories or in-depth description' (1995, p. 13). When interviewing in schools, one of the first things I was often asked was if I had been a teacher myself, where and for how long. Teachers wanted to know that I understood what it was like to be a teacher and to work in a school before they were prepared to trust me with their stories of school life; thus my teacher background gave me greater access into teachers' worlds.

The inspiration for the project came from my experience both as a secondary school science teacher and as a freelance science education consultant. As a science teacher I wanted to be part of the process of educating students and believed that education through science should include furthering students' education in literacy and mathematics as well as in science itself. I worked in four schools of varying sizes; in none of them was there a working relationship between the science and mathematics departments. I realised that students found using mathematics in science challenging and over time began to wonder whether working with the mathematics department would help students to use their mathematics more effectively. As a consultant I worked on projects researching the amount of mathematics in science assessments for SCORE (published as SCORE 2009, 2011) and on a preliminary project with the Nuffield Foundation seeking to improve relationships between mathematics and science educators, known as the STEM sharers group. From some provisional reading, I realised that the relationship between school science and mathematics education was little understood and there was scope for further research.

In the following sections, I describe the methods used to gather the data and to analyse it. I then consider the trustworthiness and the ethics of the research, and consequently of the findings.

5.2 Sampling

A two-phase qualitative approach was undertaken to explore participants' experiences and views of the relationship between mathematics and science education. Two distinct groups were approached and interviewed to try to gain insights into both the policy-making process at a national level and the realities of working in school.

5.2.1 Phase 1 – The policy makers

In phase one, semi-structured interviews were conducted between March 2013 and June 2014 with 21 long-standing and acknowledged key contributors to the science and mathematics education communities, with questions focussed around the development of the original national curriculum for England, the writing of the latest iterations of the secondary national curriculum for mathematics and science (published in 2013 and 2015), and the origins and rise of the STEM agenda in the UK.

Membership of the science and mathematics education communities is not fixed, and could be a matter for debate. Ball and Junemann (2012) argue that the UK government is increasingly using policy networks to bring new solutions to difficult problems by bringing together traditional government agencies and public bodies with private, voluntary and philanthropic organisations which have an interest in the issue at hand. The term *policy network* is contested and subject to several different interpretations (Ball & Junemann, 2012), but is used here to describe several interdependent actors from a number of different organisations involved in defining and delivering a policy agenda. These networks may be harmonious but they can be large with members only loosely connected. This type of policy making is, by its nature, rather opaque.

As Ball and Junemann (2012) note, it can be difficult to identify membership, connectivity and boundaries even of a relatively small policy network, and memberships and influence can change considerably over time. They suggest that the limits are often ‘pragmatic and reflect more the limitations of data collection […] than any firm cut-off points in the social relations between actors’ (p.10). Interviewees for this study were selected on the basis that they had had some influence on government science or mathematics education policy in the last 30 years. Among the interviewees were: at least eight people with national honours for services to education; at least three authors of government reports on aspects of education; authors of and contributors to the national curriculum; employees or former employees of learned societies and charitable trusts with an interest in science or mathematics education including the Royal Society, Royal Society of Chemistry, Institute of Physics, Nuffield Foundation, Gatsby Charitable trust, Royal Academy of Engineering, Millennium Mathematics Project, Mathematics for Education and Industry; five professors of education; former employees from the Department for Education; former employees of QCA (Qualifications and Curriculum Authority) or QCDA (Qualifications and Curriculum Development Agency); members and former members of the Advisory Committee on Mathematics Education (ACME) and Science Community Representing Education (SCORE); and members of Ofqual (the Office of qualifications and examinations regulation) committees.

Walford (2012) argues that the main difference when researching the powerful in education – which these interviewees are to a greater or lesser extent – is the need to access data from specific people. The first challenge was to identify those people. A snowball sampling technique was adopted whereby some initial interviewees were selected and each participant asked for recommendations or introductions to other potential interviewees. This is a particularly useful technique for hard to reach groups or groups where it is hard to define membership (Cohen, Manion, & Morrison, 2011), which undoubtedly applied in this case. Snowball sampling is a social technique relying on strong interpersonal relations and known contacts as well as reputational contacts. I ‘exploited pre-existing links with those in power’ (Walford, 2012, p. 112) to gain access to initial participants and then used a reputational snowball by asking interviewees to ‘identify others in the field who are particularly influential, important or worth contacting’ (Cohen, Manion, & Morrison, 2011, p. 159). The reputational snowball proved a powerful means of identifying significant contacts in what is a small network. This was particularly the case as I was researching individuals who, although they may be powerful and influential in the field of policy development, are not always known to the public (Cohen *et al*., 2011).

Following the advice of Walford (2012, p. 112) that 'researching the powerful requires many of the attributes of the social climber', anyone who might possibly be able to give introductions or vouch for me was approached and asked for help in gaining access. To try to avoid the possibility that participants would suggest others with similar views, a number of people who I did not intend to interview (including university academics and education consultants) were approached and asked for suggestions. All these additional people were known to me in some capacity and some provided introductions to eventual participants. This approach was specifically to aim for balance and to ensure both sides of any arguments were represented, as recommended by Rubin and Rubin (1995, p. 69). A number of participants were retired and Walford (2012) suggests access is more likely to such participants and they are more likely to speak freely than those still in power.

The original aim was to interview a similar number of science and mathematics educators. Probably in part due to the reputation of my supervisors and in part as I had worked as a consultant in the science education community for some years, and thus knew many of the science educators and was known by reputation to several others, most of the science educators approached agreed to be interviewed. This was not the case for the mathematics educators. Those approached who I already knew agreed to be involved, but, unsurprisingly, many of those for whom I was just an unknown science educator declined. Some of the interviewees were happy to provide an introduction to others who were unknown which did facilitate access to a wider range of participants than might otherwise have been possible. Ultimately eight mathematics educators, eleven science educators, one engineer and one retired civil servant whose background was neither science nor mathematics were interviewed. Interviewing continued until subsequent interviews, while offering interesting individual perspectives, were not offering anything that was substantively new; that is, until data saturation was reached (Rubin & Rubin, 1995). The decision to stop interviewing was taken in consultation with my supervisors.

The approach letter to potential interviewees (Appendix 2) stated that they would be asked about the relationship between school mathematics and science education and the STEM agenda. A number of those approached who declined (both mathematicians and scientists) did so due to a stated lack of interest in STEM or anything pertaining to it. A number of mathematicians declined due to a stated lack of interest in science. Thus the sample is unavoidably skewed towards those who have more positive conceptions of STEM and mathematicians who are more interested in science. This issue is addressed in the discussion of the findings.

Interviewees were not asked if they self-identified as mathematicians or scientists. Many of those with a science background would, in any case, be likely to prefer to be called a chemist, physicist or biologist rather than a scientist. Similar numbers were interviewed from each sub-specialism as a deliberate choice. An individual has been denoted a mathematician if they: have chaired or sat on the committee for a mathematics organisation such as ACME or the JMC; have a mathematics degree; have worked for a mathematics organisation; or if they have written government reports about mathematics education. Two of the eight mathematicians do not have a first degree in mathematics, however they fulfilled the other criteria.

5.2.2 Phase 2 – The schools

In Phase 2 (January 2014 – July 2015), a second set of interviews was conducted in six schools where the science and mathematics departments collaborate to some extent. This approach to working across departments is rare in England and finding such schools was challenging. The aim was to explore the perspectives of the teachers involved in collaborations about the aims of, and benefits and barriers to, such work.

The first, major, difficulty was identifying participants given that this type of collaboration is rare. NRICH mathematics, part of the Millennium Mathematics project, held a series of three workshops in 2012-13 called STEM NRICH. One of the aims of these workshops was to encourage teachers from mathematics departments in school to talk to and, perhaps, work with colleagues from other STEM departments. I was invited to attend the workshops with the specific intention of making contact with teachers from schools where there may be departments which cooperate. As a direct result of attending the workshops, I was invited into two schools. I gained access to a third as I already knew the school principal. Two school visits came from contacts that I had through other work and I made contact with one school through attending workshops relating to mathematics at the Association for Science Education (ASE) annual conference and talking to the teachers present. As schools are often understandably reluctant to allow access to unknown researchers, the time taken in making personal contact with potential participants through work, conferences and workshops was invaluable for both identifying potential schools and gaining access to them.

The process outlined above is an example of purposive sampling – examples picked because they possess the particular characteristics being sought. The cases required are highly unusual so there is no pretence that they represent the wider population of schools; the choice is unashamedly selective (Cohen, Manion, & Morrison, 2011). However, to ensure that there is some generalizability to the average secondary school, very unusual schools (such as a very small, Christian independent school which was willing to be involved) were excluded from the sample even if their mathematics and science departments were working together. The schools are drawn from a wide geographic area and have a range of intakes. The decision was also made to limit the number of schools contacted via the NRICH programme to two as the type of collaboration they have is quite similar; this has helped to ensure that the sample is not skewed towards a particular style of collaboration that NRICH might encourage. The variation in where schools are drawn from is important as this study is unusual in its focus on collaborations which have developed organically between mathematics and science departments in schools in England, rather than as the implementation of a specific programme devised by researchers.

My original intention was to interview the head of science, head of mathematics and a member of the senior leadership team in each collaborating school. It became apparent, however, that these were often not the people most closely involved in the collaboration and in only one school were people who held these three posts interviewed. In two schools a key person involved in the collaboration had left and in these schools there was only one participant. While I would have preferred multiple perspectives to each collaboration, these two schools provided important insights, particularly into how and why collaboration can reduce or even cease and thus are included even though they did not quite fit my original research design.

5.3 Interviewing

> A research interview is an interpersonal situation, a conversation between two partners about a theme of mutual interest. (Kvale & Brinkmann, 2009, p. 123)

To enable such a conversation to develop, the interviews were as open-ended as possible to allow 'respondents to demonstrate their unique way of looking at the world – their definition of the situation' (Cohen *et al*., 2011, p. 205). As such, the sequences of questions and exactly which questions were asked varied between interviews. Interviews started with questions which would put people at their ease, particularly those people who were not known to me, recognising that 'what is a suitable sequence of questions for one respondent might be less suitable for another' (*ibid*.). This variation between interviews is also recognised by Rubin and Rubin: 'the content of the interview, as well as the flow and choice of topics, changes to match what the individual interviewee knows and feels' (1995, p. 6). The open-ended nature of the interviews also allowed important but unexpected issues which were raised to be followed up. When trying to find out what happened and why people acted in the way that they did, Rubin and Rubin (1995) argue that it makes little sense to ask everyone the same questions as the goal is to gain a rich description of people's perspectives in individualistic terms. Leading questions were avoided as far as possible and after each interview the responses were examined to see if the questions were yielding the kind of data hoped for, with the questions being adapted as necessary. A common sequence of questions – about STEM – was included within each policy-maker interview largely unadapted (Appendix 3) so that there were some questions common across all interviews, allowing norming of the answers to at least some degree as suggested by Rubin and Rubin (1995, p. 84). Some of the points raised by interviewees were incorporated into subsequent interviews in an iterative and self-correcting design (Rubin & Rubin, 1995).

The key difference between interviewing many of the policy makers and interviews conducted in schools was the level of preparation which was required. People who occupied a position of some importance or who had published material on a topic expected, understandably, that I would know about their work in some detail. The more I knew in advance about the projects and work they had been involved with, the more detailed their answers tended to be. There was far less available publically about the specific collaborations in schools, or about the teachers themselves, and teachers therefore did not expect me to know about their prior work. Consequently, the interview schedule for schools (Appendix 4) varied less, but unexpected issues were followed up in the way that they were for the policy makers.

The original study design called for entirely face-to-face interviews, but the contingencies of the data collection meant that telephone interviews were used for three of the policy makers. These were due to interviewee preference and covered one ill and two retired interviewees. Sturges and Hanrahan suggest that:

> Telephone interviewing may provide an opportunity to obtain data from potential participants who are reluctant to participate in face-to-face interviews [...] In these cases, use of the telephone could make it possible to obtain data from people who would not otherwise have their views represented. (2004, p. 109)

This was indeed the case for these participants, and the data gathered as a result added new insights and depth to the picture being built up. Sturges and Hanrahan (2004, p. 108) concluded that in their data there was no significant difference between the telephone and face-to-face interview data and therefore that telephone interviewing can be used successfully in qualitative research. Overall, though, face-to-face interviewing was used wherever possible, as not seeing the participant deprives the researcher of access to any non-verbal communication during the interview – but all interviews were analysed in the same way (by transcript) so it affected only the actual interview and not the analysis.

Many of the interviewees, from both groups, commented afterwards that they had enjoyed being interviewed, suggesting that the interviews were genuinely ‘a conversation between two partners about a theme of mutual interest’ (Kvale & Brinkmann, 2009, p. 123). Kvale and Brinkmann suggest some criteria to judge the quality of an interview. They include:

- The extent of spontaneous, rich, specific, and relevant answers from the interviewee
- The extent of short interviewer questions and longer interviewee answers
- The degree to which the interviewer follows up and clarifies the meanings of the relevant aspects of the answers
- The interviewer attempting to verify his or her interpretations of the subject's answers over the course of the interview. (2009, p. 164)

As with Sturges and Hanrahan (2004), the nature and depth of the responses of telephone interviews did not differ significantly from the face-to-face interviews. The total length of the telephone interviews fell within the range of the face-to-face interviews; the shortest of the interviews conducted were face-to-face. Thus the lack of visual clues during the interview did not apparently affect interview quality (as judged by the criteria above) and allowed access to participants who would not otherwise have taken part in the study.

The remainder of the interviews were conducted at a time and place of the participants’ choosing; some in the interviewee’s workplace, some in my office, some in another location chosen by the interviewee. Judging again by Kvale and Brinkmann’s (2009) criteria, and in particular the length and depth of the responses, the location did not appear to influence the quality of the interview. All the school interviews were conducted in the school and face to face. Most were conducted individually, although in some there was overlap with two participants present for part of the interview, and the science teacher from Beebury was present for the whole of the interview with the Principal, with that interview becoming more of a three-way conversation.

Nine of the policy maker interviewees and two of the teacher interviewees were previously known to me and were thus what can be termed 'acquaintance interviews' (Garton & Copland, 2010). The majority of these acquaintance interviews proceeded in a similar fashion to the non-acquaintance interviews, but in at least one it was difficult to get the interviewee to talk in detail about events and happenings that he believed I already knew about. Thus the quality of the data was not as high as it might have been as only the audio-recorded information counts as data, not any prior knowledge from other sources (Braun & Clarke, 2013). This was a small price to pay for the ability to access interviewees who might not have been available without prior acquaintance. Garton and Copland (2010) suggest that data in acquaintance interviews are generated in a particular way which allows acquaintances access to data which 'might not be available to researchers who do not share similar backgrounds with their informants' and that this data is not 'in anyway more valid (or invalid) than data collected in more traditional interview settings' (p. 548).

These differences between each interview could be considered to be a short-coming of the method used, but as there are:

> many factors which inevitably differ from one interview to another such as social distance, mutual trust and the interviewer's control […] It is impossible, just as in everyday life, to bring every aspect of the [interview] encounter within rational control. (Cohen *et al*., 2011, p. 410)

It is thus probably chasing a chimera to try to suggest that the conditions of each interview should be identical. Judging by the Kvale and Brinkmann criteria, the interviews were of high quality and the quality did not vary by location, mode or whether they were acquaintance or stranger interviews. The point is that everything possible was done to ensure that each interview was full of rich, specific and relevant answers and that each interviewee was treated as an individual, in a way which made them feel comfortable and at ease.

5.4 Data analysis

5.4.1 Transcription

Interviews, both telephone and face-to-face, were recorded using an Olympus Digital voice recorder following interviewee consent. Interviews were transcribed and analysed throughout the data collection process. I transcribed some initial interviews in order to listen in detail to how the questions were being answered. Subsequent interviews were transcribed (intelligent verbatim) by a professional transcription service. I checked all transcriptions very carefully against the original recording and then deleted the recording. All interview transcripts are stored on password protected devices and were encrypted when sent electronically, for example to my supervisors.

'Transcriptions are translations from an oral language to a written language' (Kvale & Brinkmann, 2009, p. 178) and there can be no true, objective transformation from the oral to the written mode. Even the recording is an impoverished record of a face-to-face encounter where there may be much non-verbal communication. Nevertheless, these good quality transcripts were powerful tools for analysing the collected data.

5.4.2 Coding

The two data sets were analysed separately but both using thematic analysis, seeking to understand a phenomenon as it appears within the dataset collected, as described by Braun and Clarke (2006, 2013). The first step involved immersion in the data through checking the transcript against the audio-recording followed by repeated reading of the transcripts. Note was made of potential items of interest.

The data were then coded using a complete coding process (a sample of the coding is given in Appendix 5). A code is 'a word or brief phrase that captures the essence of why you think a particular bit of data may be useful' (Braun & Clarke, 2013, p. 207). Initial coding of three or four transcripts was done by hand to try out different codes and to see how they worked. The whole data set was then uploaded into NVIVO 10 and subsequent coding and data management was carried out using this software. A mix of inductive (based on the data set) and deductive (based on the theoretical framework from chapter 4) codes were used (Braun & Clarke, 2006). Following Charmaz, (2006) initial coding was done quickly and largely spontaneously.

Some large lump codes (Saldaña, 2009) were used initially such as 'relationship between mathematics and science communities'. In subsequent rounds of coding these were broken into smaller codes to get a more fine-grained picture of the data. There were some instances of simultaneous coding, where one piece of data is assigned more than one code (Saldaña, 2009). Coding was done widely and comprehensively with the majority of the data being coded, as recommended by Braun and Clarke (2013).

In total, around 100 codes were generated for each data set (Appendices 8 and 9). As it is difficult to hold that many codes in one's head at a time, several codes began with the same word (such as STEM) and the codes arranged alphabetically in NVIVO, allowing for easier navigation of the code list. A code book was written and stored within NVIVO detailing each code, when it should be used and, for some, when it should not be used to help keep coding consistent (Appendices 8 and 9). The code book was scrutinized and those codes which seemed to be the same or overlap were either combined into one or re-defined. Most codes were evident in more than one interview and some were present in most interviews (Braun & Clarke, 2013).

Attribute codes were also entered (Saldaña, 2009), with each interview coded for scientist/mathematician/other, subject of first degree where known, interview date, interview mode – face-to-face or telephone – and school for the teachers. Throughout the process, notes were kept about coding decisions taken, particularly when codes were expanded or collapsed, with reasons for doing so being documented. These notes and coding decisions were regularly discussed with colleagues and my supervisors.

Once the process of coding seemed to be largely complete, codes were pulled from NVIVO into Excel. Each instance of each use of each code was checked against the description from the code book to ensure that it was a genuine fit for the code. Where there was conflict, pieces of data were removed from the code or the code description was re-worded and NVIVO updated. This process was carried out for each of the 100 codes in each data set. A summary was then written for each code detailing what it showed. If the summary contained too many points or required a lot of detail then the code was re-examined to see if it would be better split. A number of the codes together with samples of data from within that code were presented in a research group meeting. The similarity of the data to each other and the code name were commented on by other members of the team, who concurred with the codes and the coding. As there was only one person carrying out all the coding there was no need for an inter-rater reliability check.

5.4.3 Identifying patterns

In coding, the interviews are torn apart into little pieces. In identifying patterns the data are put back together to tell a coherent story. Two concepts were at the heart of the identification of patterns and themes:

> Pattern-based analysis rests on the presumption that ideas which recur across a dataset capture something psychologically or socially meaningful. (Braun & Clarke, 2013, p. 223)

> A theme captures something important about the data in relation to the research question, and represents some level of patterned response or meaning within the data set. (Braun & Clarke, 2006, p. 82)

In the next phase of the analysis, themes were developed from the codes and coded data. Following Braun and Clarke (2006, 2013), concepts, topics or issues which several codes were related to were searched for. Mind-mapping was used to try to make sense of the codes, and a number of mind-maps were drawn to help make sense of the data (for an example see Appendix 8). Mind-mapping and the search for relevant themes is acknowledging that 'Qualitative research is not about finding the right answer; what you're looking for is the best 'fit' of analysis to answer the research question' (Braun & Clarke, 2013, p. 230). The mind-maps were then used to help draw up coding trees (an example is given in Appendix 9). The coding trees were pruned and codes which did not add anything helpful to the overall picture were removed, particularly if the data captured in that code was also coded for elsewhere, or amalgamated.

Four key themes emerged from this process: power; policy; transfer; and identity and beliefs. Although each data set was analysed separately, it became apparent that the themes of power, policy and transfer could be applied across both data sets. Where themes appeared in both data sets, the data comprising each theme was compared across the two data sets and particular attention was paid to the similarities and differences between them.

5.4.4 Writing and communicating the research

Braun and Clarke (2013) argue that writing is part of the process of qualitative research, used to generate, rather than simply report, ideas because qualitative analysis *is* writing. It is a way of thinking, a messy and iterative process, a way of finding the argument you are trying to make. I have certainly found writing to be all of this and more in producing this thesis. While the mind-maps and the coding trees were helpful in making sense of the data and identifying the themes, it is in writing that I made decisions about what to focus on and, indeed, what to leave out. Decisions made about the writing are, therefore, decisions made about the analysis of the data: the two are inextricably linked.

5.5 Ethical considerations

> An ethical dilemma occurs when a researcher encounters a situation in which he or she is not sure how to act to protect and promote the interests of all participants in a study. (Tobin, 1992, p. 113)

To try to minimise any ethical dilemmas during the course of the study, BERA's (2011) and King's College London's ethical guidelines were consulted and procedures put in place and followed to ensure a duty of care to all the participants. This research was ethically approved by King's College London, with two years' approval initially sought. Approval was granted in 2013 (reference number REP(EM)/12/13-26), and an extension granted in 2015 which allowed me to complete interviews in the final two schools.

This study involved interviews with a number of prior acquaintances. There is very little written about interviewing acquaintances (Garton and Copland, 2010, is one example) and even less about the specific ethics of interviewing acquaintances. McDermid, Peters, Jackson and Daly (2014) offer an example from the field of nursing, but there do not appear to be many papers specifically about this issue from the perspective of educational research. This lack is perhaps surprising as Walford (2012) suggests that to gain access to those in power it is helpful to exploit 'pre-existing links,' in other words acquaintance-ship, and also notes that education researchers often choose particular schools as they are convenient, local and, pertinently, known to the researcher or contacts can be made through colleagues or friends (Walford, 2005). In this study, care was taken both to keep respondents as anonymous as possible and to ensure that interviews were set up to be professional.

Another ethical implication is that a school may be relatively easy to identify even if it is not named in the final publication. This and other ethical implications of using easy-to-reach schools are not often discussed in educational research. There is more written about the ethics of interviewing elites in education (for example Walford, 2012) and so I consider the ethical implications for each phase of the research separately below.

I tried to follow at all times the principle of *primum non nocere* (first of all, do no harm). For the schools phase of this study I deliberately used schools which are far apart and gained access to them through a variety of channels rather than relying on schools which have close links to one of the two universities where I worked through the duration of the study. As the schools are widely spread geographically, and I have included as few significant identifying features as I can, I am reasonably confident that the schools will not be easily identifiable. This did entail, as Walford (2005) suggests, increased cost of the research in terms of travel times, travel cost and, on occasion, overnight accommodation. It does mean I am confident that I have done all that I reasonably can to preserve the anonymity which I offered to the participating schools. Any details which might potentially identify the schools were discussed with my supervisors before inclusion. An additional ethical consideration is that of what was said in individual interviews which could have the potential to cause dissent within the school. In most schools I interviewed more than one person and each person interviewed knew who else I had spoken to, largely as they were the people most closely involved in the collaborative projects. This would be contrary to what would be expected in medical research as described by McDermid *et al*. (2014), who argue that participants should not know who else is participating, and shows how different norms apply in different research settings. There are different degrees of anonymity (Wengraf, 2001) and I anticipate that participating teachers will be able to recognise themselves and therefore their colleagues in what is written and thus care was taken in reporting, for example, descriptions of friction or frustration between colleagues and school departments. Such relationships can be fragile, as this study shows, and I would not wish participation to lead to further tensions so I was very careful in the details I included.

For the policy makers research, I originally asked permission to name the respondents and interviews were conducted on that basis. This was in part so that I could demonstrate through the use of names that I had indeed contacted people who were at the heart of the science and mathematics education community. Walford (2012) notes that this is often central in policy research and Ball (1990) named many of his participants in his study of the development of the national curriculum. I gave participants the option to request anonymity but few chose to do so, although some did ask to see what I was quoting them as saying prior to publication. It was following discussion with international colleagues, who were very interested in the findings from the research but not at all interested in the names of those interviewed, that I made the decision to anonymise the data. Anonymity is the norm in educational research (BERA, 2011). Due to the snowball sampling technique to gain access to participants, however, it would be impossible to guarantee that individuals could not be identified by others in the field. By the very nature of the technique other interviewees will know at least who some of the other individuals in sample are and may have provided introductions to them. Furthermore, when participants are senior and have something significant to say they are in some cases bound to be recognisable by others in the field. However, gaining consent to name the people involved has alerted participants that what they say may enter the public domain and become known to their peers; they can therefore be careful what they disclose in the interview. They also entered into the interviews knowing that their responses would be published in a PhD thesis and potentially in other academic outputs. I have at times aggregated data and, in selecting quotes for inclusion, have tried not to cause potential harm to existing relationships. Where data is more sensitive or discrediting I have been especially careful and where people requested anonymity I have been particularly careful to try to preserve it.

On submitting a paper for publication based on the policy participants (Wong, Dillon, & King, 2016), the reviewers asked for further details of the participants including age and sex. I refused and have deliberately chosen not to give such details as, in a small field, this would allow identification of the participants by anyone reasonably competent at using an internet search engine. I have referred to each by a two or three letter code and given the barest details about some of the activities in which they have been involved. Such decisions could lead to concerns about whether the data lose some of their 'richness' and become too thin (Cohen, Manion, & Morrison, 2011). There is therefore sometimes a tension between ethics and the reporting of the research. Walford acknowledges that:

> While it is ethical to take extreme care with interpretation, there may be a conflict with another ethical duty to report what has been said. (2012, p. 114)

Are there particular ethical issues where the participants are prior acquaintances, or is it just that it is easier to be aware of them? For example, it is possible that if one is likely at a later date to meet the people interviewed, or who have effected an introduction to a participant, that one might be even more careful to 'do no harm'. It is possible to see how this could raise dilemmas, for instance if the research uncovers information which the prior acquaintance would rather remained concealed.

Walford argues that the ethical issues with interviewing those in powerful positions are not so different to those for other interviews:

> The ethical problems involved in interviewing anyone are similar to those interviewing the powerful. Research often involves revealing secrets, and making public information that some would not like it to be made public. […] ethically, the problem of what information is to be made public is the same. Researchers often do not bother to get respondent validation from those without power or seek to see whether they agree with any analysis but, ethically, there is just as much of a problem in misrepresenting an unnamed person as with misrepresenting a named one. (2012, p. 116)

Cohen, Manion and Morrison (2011) also argue that individual researchers have a responsibility to the wider research community, by not jeopardising the reputation of the research community or spoiling opportunities for further research. Some of the participants from both phases in this study had taken part in earlier research projects. If they had had negative experiences on previous occasions it would have made it far more difficult, or even impossible, to gain their consent to contributing to this project.

5.6 Participants

5.6.1 Policy maker participants

I have given each of the policy maker participants a two or three letter pseudonym to maintain anonymity. The first letter represents their discipline (mathematics, science, engineering, civil service), the second a letter to identify them. The interviews were carried out on the dates given below.

Disciplinary background	Pseudonym	Date of interview
mathematics	MA	25/03/13
	MB	25/04/13
	MC	23/09/13
	MD	08/10/13
	ME	14/11/13
	MF	25/11/13
	MG	21/02/14
	MH	08/05/14
science	SA	26/03/13
	SB	30/05/13
	SC	02/07/13
	SD	09/07/13
	SE	26/06/13
	SF	02/07/13
	SG	16/07/13
	SH	15/08/13
	SI	13/03/14
	SJ	24/03/14
	SK	06/04/14
engineering	EA	01/07/13
civil service	CSA	10/09/13

5.6.2 School participants

I have given each of the participants a two or three letter pseudonym to maintain anonymity. The first letter represents their school (A-F, all pseudonyms), the second their disciplinary background (mathematics, science, technology), and an L denotes a senior leader. All interviews in any given school were carried out on the same day, dates for each are given below.

School	**Date of interview**	**Disciplinary background**	**Pseudonym**
Ayford	09/01/14	mathematics	AM
		science	AS
		technology	ATL
Beebury	22/01/14	mathematics	BM
		science	BS
		science	BSL
		technology	BT
Ceeton	27/01/14	mathematics	CML
Deecom	15/12/14	science	DS
Eyston	30/04/15	mathematics	EM
		science	ES
		science	ESL
Effdon	09/07/15	mathematics	FM
		mathematics	FML
		science	FS

I have thus described and explained the methods and the methodology of the study and in the next three chapters I present the findings. Chapter 6 contains a rich description of the six collaborating schools and their collaborations. In Chapter 7 I use the lenses from the theoretical framework to explore the findings from the schools, and in Chapter 8 use some of those lenses to explore the findings from the policy makers.

Chapter 6
Collaboration in Schools

As I explained in Chapter 5, finding schools where science and mathematics departments collaborate was challenging. In this chapter, I describe the six participating schools and the types of collaboration in each. I will show that collaboration is possible, and that certain types of collaboration make curriculum sense and are valued by teachers. Collaboration is, however, fragile and moreover it is not as straightforward as is sometimes assumed for mathematics and science teachers to find meaningful points of overlap between their curricula.

6.1 The schools

6.1.1 Ayford School

Ayford School is a large, mixed, semi-rural 11-18 comprehensive school with a low proportion of pupils eligible for free school meals. It is an academy and part of a small, fairly local, group of academies run by an executive principal, with day-to-day running overseen by a deputy headteacher.

The three participants interviewed were:

- 'AM', AST (Advanced Skills Teacher) mathematics
- 'AS', head of physics
- 'ATL', deputy headteacher, engineer and teacher of design technology (who has also taught both mathematics and science)

The collaboration at Ayford is very much driven by AM, an Advanced Skills Teacher and former head of mathematics. AM predominantly collaborates with AS, the head of physics. Their collaboration came from working with a Cambridge University Millennium Mathematics Project initiative, STEM NRICH. AM had worked with NRICH on previous projects and asked AS to get involved with this one as a STEM colleague from another department was needed. They had been working alongside NRICH in the development of resources to support STEM collaboration and spoke about the work they had done together at some of the STEM NRICH Continuing Professional Development (CPD) courses and at other conferences. AS successfully used the work for a master's thesis.

AM and AS mainly worked with key stage 3 pupils. They co-organised a joint project for Year 9 students across the mathematics and science departments and visited each other's lessons to do short inputs on maths into a science lesson or science into a maths lesson (which they called ‘visiting expert’). Additionally, they organised a joint lesson across mathematics and physics for Years 11 and 12 with the aim of encouraging students to think about studying physics and mathematics post-16. The rest of the mathematics and science departments were involved with the joint project, but aside from a joint meeting to set up that project there is limited other collaboration.

The deputy head, ATL, explained that the school likes to allow its teachers a degree of autonomy and as AM was interested in setting up collaborative ventures they allowed it, but they did not explicitly encourage it. AM was also working on a joint bid with the design technology department for a 3D printer.

6.1.2 Beebury Academy

Beebury Academy is a large, mixed, urban 11-18 comprehensive school with a high proportion of pupils eligible for free school meals. It is part of a national chain of academies, with a principal responsible for running this school only. The school is arranged as three faculties, one of them being science, mathematics and technology (MST). The school also teaches engineering from 14-16 and in the sixth form.

The four participants interviewed were:

- ‘BSL’, principal, biology teacher
- ‘BS’, vice principal, head of MST (mathematics, science and technology) and chemistry teacher
- ‘BT’, head of year 7 and 8 MST who oversees the integrated curriculum, technology teacher
- ‘BM’, numeracy coordinator (effectively head of year 7 and 8 mathematics), mathematics teacher

The school has a brand new building specifically designed to allow for collaborative and integrated teaching. There is no staff room, with staff encouraged to use the student restaurant, where free coffee is provided, for conversations. There is a small workroom in each faculty. The backbone of the school has impressive IT and technology facilities, science laboratories, a library and offices, with MST having its own separate wing leading off from this backbone. The MST teaching rooms are in groups of four with flexible walls which can be opened up to form a large space to accommodate the equivalent of two or four classes (60 or 120 students). All these MST rooms have electronic white boards, with the computer at the back to discourage staff from sitting at the front behind a desk. The rooms are carpeted and have only a single sink and no gas taps.

Key stage 3 is taught in these rooms as an integrated MST curriculum by staff from any of the disciplines of mathematics, science and technology. Following some disappointing GCSE results, all students now have some separate mathematics lessons during Year 7 and 8 and they were also planning to begin having some separate science lessons the following year. Some of the separate mathematics lessons are taught by science specialists. There were strong disagreements about breaking down the integrated curriculum that was seen as being at the heart of the academy's identity, including disagreement about whether the integrated curriculum was to blame for the disappointing results.

6.1.3 Ceeton Academy

Ceeton Academy is a fairly small 11-18 state school with a large proportion of pupils eligible for free school meals and large proportion of students from ethnic minority backgrounds. Science and mathematics are in a faculty (a 'zone') together with PE (physical education) and design technology; this is known as the 'practical zone'. They are part of a local sixth form consortium.

The one participant interviewed was:

- 'CML', assistant principal and head of the practical zone, mathematics teacher

The school has a new building which it moved into as part of the then Labour government's (now-defunct) 'Building Schools for the Future' programme. The school was designed to allow for collaboration between the groups of subjects in each zone. There is a zone staff room but no central staff room. The science laboratories have the expected facilities but, more unusually, both science and mathematics teaching rooms have glass walls looking onto the corridor so anyone passing can see what is going on. As does the office of CML, but this has been covered with posters to make it 'less like a goldfish bowl'.

Mathematics and science are taught separately by subject specialists, but during the first half term of Year 7 all students follow a practical zone project (see appendix 10 for project details), with the school timetable designed to allow this to happen. As the teachers were concerned about student progress in that first term, all students also have one lesson each week of mathematics and science which are not part of the project.

Other collaboration is largely organised by a teacher who is designated as a *STEM lead* to coordinate and to promote STEM across particularly mathematics, science and design technology. This STEM focus has included starter activities with photographs and the question 'where's the STEM?', joint visits, and extracurricular activities such as a STEM club. They have also sent several members of staff to the STEM NRICH days in Cambridge. There has been discussion between A-level mathematics and physics teachers about the teaching of mechanics. They have also tried using the ‘visiting expert’ model similar to that tried in Ayford, but CML reported that it has not really caught on. The STEM lead was a post designed to keep a talented teacher in the school and when they moved on there was a significant reduction in collaborative activity in the faculty, although another STEM lead was appointed.

6.1.4 Deecom College

Deecom College is a relatively large, mixed, 11-18 school in a small town, with a low proportion of pupils eligible for free school meals and a falling roll due to the demographics of the town. Subjects are taught by specialists, with science teachers mainly teaching their (biology, chemistry, physics) specialism from key stage 4. There are two science teachers who also teach mathematics which helped to avoid redundancies in science while at the same time filling much needed vacancies within mathematics. The falling roll (and consequently lower budget) has also led to the loss of a post-holder within science. The headteacher was previously a physics teacher.

The one participant interviewed was:

- ‘DS’, head of science

The collaboration here has involved joint projects between the mathematics and science departments. The first was a Year 7 project based on Hooke’s law, which DS described as a mathematics project that science helped with. Students did practical work with springs and weights in science with the data analysis followed up in mathematics (see Appendix 11 for the student project booklet). This project had not run for some years, but DS had all the information and booklets and suggested it would be relatively easy to set up again, although there were no plans to do so.

The second was a Year 8 project which had started due to the enthusiasm for cross-departmental collaboration of a deputy headteacher (who had left the summer before I visited). The school had received some money through a programme called ‘Change Schools’ specifically to foster collaborative work and the mathematics-science collaboration was one of the outcomes. The money was used to pay for a planetarium tent and a 9-metre rocket to come to the school. Additionally, all Year 8 pupils visited the National Space Centre and these three activities formed the basis of a project about space. It took place towards the end of the summer term and had an open style of teaching with pupils working at their own pace in both their mathematics and science lessons (see Appendix 12 for the project details and learning objectives).

The funding has ended, the deputy head has left, science has lost a post-holder and directly as a result of these three factors the project is no longer being run. DS still has the information but noted that this project took far more work and effort than the Year 7 project and is unlikely to be revived in the near future, particularly as departmental collaboration is no longer a school priority.

6.1.5 Eyston House

Eyston House is a small 3-16 girls' independent (fee-paying) day school. Most staff teach in either the junior (7-11) or senior (11-16) departments but there is some cross over. Science and mathematics are in a faculty together, led by the head of science. The two were separate departments but the head and the head of science had moved the mathematics department to be next to the science department specifically to encourage collaboration some years earlier. The headteacher had been a physics teacher.

The three participants interviewed were:

- 'ESL', headteacher, former physics teacher
- 'ES', head of science and mathematics faculty, science teacher
- 'EM', head of mathematics

Having the two departments next to each other had facilitated and encouraged informal conversations and these conversations were both the start and the heart of the collaboration. Most mathematics staff stayed in the prep room for break time and spent their time talking to the science staff. Talking about difficulties in teaching aspects of the curriculum, about individual pupils and about how to overcome some shared problems had led to the production of a more formal, although short, policy (in Appendix 1). This policy set out what language would be used for various aspects of science and mathematics to ensure consistency. They also shared some equipment including some bought with money that had been received for additional external work undertaken jointly by the departments.

6.1.6 Effdon School

Effdon School is large, mixed, 11-18 urban school with a high proportion of pupils eligible for free school meals and a high proportion of pupils with special educational needs (SEN).

Science and mathematics are separate departments but are sited fairly close to each other on the large school site.

The three participants interviewed were:

- ‘FML’, vice principal, former head of mathematics
- ‘FM’, mathematics teacher, overseeing mathematics-across-the-school, physics degree
- ‘FS’, head of science, physics teacher.

The school had begun a push on ‘mathematics across the curriculum’ to build on existing work on ‘literacy across the curriculum.’ Mathematics across the curriculum was begun by FML, a vice-principal and mathematics teacher, but mainly implemented by FM as a ‘development opportunity,’ in other words, unpaid extra work. They began with questionnaires to find out from pupils and teachers the areas where students struggled and the aspects of mathematics they were being expected to use in other curriculum areas which they found hard. These were collated and used to choose 12 focus areas such that across Years 7 and 8 there would be a focus on a mathematical skill each half term across every curriculum area. The collaboration was very much owned by the mathematics department and was in its early stages. Both science and mathematics teachers could talk about areas where they would like to collaborate further and how they planned to go about doing so. FS was taking account of what they had learnt from the questionnaires and from conversations in the planning of the new science curriculum.

All three of those interviewed talked about the school’s focus on literacy and the need for this to be balanced with some whole school work on mathematics. They all believed mathematics was seen as a lower priority by the headteacher as the mathematics GCSE results were better than the English results.

6.2 The collaborations

Although each school enacted collaboration in a unique way, various types and styles of collaboration could be identified.

Type of collaboration	Schools
One-off joint projects	Ayford, Ceeton, Deecom
Integrated teaching through longer projects	Beebury
Visiting expert	Ayford, Ceeton
By informal conversations	Particularly Eyston, but all except Deecom
Through school trips	Ceeton, Deecom, Eyston
In the curriculum and scheme of work	Beebury, Eyston, Effdon
Combined year 11 and 12 mathematics and physics lesson	Ayford

Table 6.2 Types of collaboration

6.2.1 Joint projects

Projects which were run across mathematics and science were what most people conceived of when asked about mathematics-science collaboration, showing similar issues with terminology as identified in the integration literature (for example by Berlin and White, 1995, and Koirala and Bowman, 2003).

Ayford, Ceeton and Deecom had all run joint projects; Beebury took the joint projects further and had all of Year 7 and 8 science, mathematics and technology taught in an integrated way through projects and themes and is therefore considered separately.

6.2.1.1 Ayford

At Ayford they had run a week-long joint project for all of year 9 in two successive years. Although called a STEM project, it was actually a mathematics and science project based around whether a bath would cool more slowly with bubbles. Work was divided clearly between what had to be done in science and in mathematics in successive lessons. AM and AS wanted to include the data handling cycle for mathematics and investigations for science and to produce data which could be used with both a mathematics and a science focus.

AM was keen to ensure students understood the similarities but also the differences between how mathematics and science would process and make sense of the data so students' graphs were photocopied and they did different things with them in each subject. AM and AS described many of the problems encountered as logistical. Students are not in the same groups for mathematics and for science and so would arrive in lessons having got to different places in the work depending on which set they had been in. This variation made life difficult for the teachers and consequently for the two leading the project who had to deal with their complaints. These difficulties were given as the main reason why the project had not been repeated in a third year and there were no plans to run it again. Furthermore, they had struggled to find a context for the project and were not satisfied with the one chosen, feeling it was rather simplistic.

6.2.1.2 Ceeton

At Ceeton the joint project was between mathematics, science, technology and PE, and lasted half a term at the start of Year 7. The project was about making smoothies, a blended fruit drink, with statistics in mathematics and digestion and energy in science. CML was not entirely happy with the context of the project. In the first year all Year 7 were timetabled into the zone at the same time, making the project logistically easier than in the next year when they were not. The original idea was that teachers from different disciplines would team-teach, but in the end it was decided that it would be easier to deliver if the content was split between the different subjects. Keeping the content for each subject relatively self-contained avoided the problems with different groups found at Ayford. Teachers were reported as happy with the project and it was expected to be run in future years.

6.2.1.3 Deecom

Deecom had had two separate projects. A simpler one for Year 7 involving Hooke's Law had been dropped some years earlier. The Year 8 project involved several lessons across both mathematics and science. Students had a booklet and were expected to work largely independently to research and complete the work, which could be done in either mathematics or science. As students worked through in their own time across both science and mathematics lessons, the teachers had to be able to explain and support the learning of both subjects. As it was a science-focused project this was felt to be particularly challenging for the mathematics teachers. The project began with the science context to which the mathematics was added, identified by both Pang and Good (2000) and Frykholm and Glassom (2005) as a common approach in planning joint projects.

Different setting was once again identified as a barrier to be overcome. At Deecom they had tried rearranging classes for the duration of the project, but this had not been successful and caused difficulties with classroom management as teachers did not know the students in front of them. Issues with behaviour management were likewise identified by Czerniak and Johnson (2014) as a barrier to integrated teaching. In a subsequent year, students had to pick a project partner who was in both their science and mathematics class and although this helped with the behaviour management it constrained student choice. Not all students responded well to the increase in responsibility they were given for managing their own learning and the difficulties this caused had never been resolved. The project did not, therefore, necessarily increase student engagement with school, although increasing engagement had been suggested as a key reason for integrated projects by Venville *et al*. (2002). The project had ended with the end of the funding and the loss of a post-holder in science and DS felt that the school priorities had moved away from wanting interdisciplinary work to focus on other things and thus it would probably not be revived.

6.2.2 Integrated teaching

The integrated teaching at Beebury effectively involved extending the joint projects idea to encompass all of the mathematics, science and technology teaching in Years 7 and 8. Students are taught through projects or units which are planned by a team of 3, a teacher from each of mathematics, science and technology. Those teachers decide both the science content and the competencies from the ‘Opening Minds’ curriculum (RSA, 2017) which will be taught through that unit. The class teacher can decide the learning objectives. Planning is now less detailed than in their early years of this approach as they had realised that teachers need to have some ownership over what they are doing with their classes or it is demotivating. In the early years the projects were based mainly around the Opening Minds competencies but they acknowledged that content was sometimes lost in the process. It was mentioned that healthy eating was studied several times, which was demotivating for students and frustrating for the teachers. They were making efforts to tighten up the content and increase the rigour of what they were doing, but not all staff agreed with this approach. They were very clearly enjoying their freedom as an academy to choose their own curriculum at key stage three.

There was the recognition from all the Beebury participants that teaching integrated MST in this way is very challenging for many reasons, including that it challenges secondary teachers’ identities as subject specialist teachers as well as requiring them to teach material that they may well not be familiar with, both identified by Venville *et al*. (2002) as challenges for integrated teaching. The principal had decided that the following year they were going to have more separate mathematics and science lessons, with fewer integrated lessons, as there were concerns about pass rates at GCSE not being high enough. Although they could not definitively link low pass rates to the integrated curriculum it was believed by the principal to be a possible reason for students making insufficient progress.

6.2.3 The Visiting Expert

The 'visiting expert' model for collaboration had been developed at Ayford School with AM and AS. They spoke about it at the STEM NRICH teacher inspiration days and Ceeton Academy had picked up and tried out the idea, with some apparently small but significant alterations.

6.2.3.1 Ayford

For AM and AS, 'visiting expert' was a quick and simple way to collaborate which did not take up too much time, in contrast to the joint project. It involved one of them going into the other's lesson to do a 5-10 minute introduction to an aspect of mathematics which would be used in science or *vice versa*. Two examples were given: AS had talked about mirrors and reflection and set up a problem for AM's lesson about symmetry. AM had talked about calculating the volume of complex shapes by approximating to a straightforward shape as an introduction to AS's lesson on lung capacity. Although they had not used 'visiting expert' extensively, both felt that even occasional use was beneficial to them and their students. In each case, there had been some prior planning before the lesson visits. In fact, they found that finding worthwhile examples for the visit could be challenging. Both recalled that when AM originally asked for contexts for teaching symmetry AS struggled to think of any, eventually deciding on angles of incidence and reflection. While clearly an example of symmetry, angles of incidence and reflection would not often be described that way in science. These communication difficulties are an example of the difference in discourse described by Bernstein (2000) and identified by Williams *et al.* (2016) as a barrier to collaboration.

6.2.3.2 Ceeton

At Ceeton, the close proximity of departments and the glass walls of the classrooms allow people in classes to see others passing in the corridors. CML noted that these glass walls were useful as they allowed staff to 'pull in' passing teachers to use them as 'visiting experts'. However, CML acknowledged that many staff found being put on the spot like this stressful in case they did not know the answer to the question being posed in front of the class. This is a significantly different approach to the advanced planning preceding the ‘visiting expert’ at Ayford, where AS was happy to admit that it had taken several minutes’ discussion and thought to answer some of the questions posed by AM. There is a real difference in having these discussions in the staff room to having them in front of a class.

6.2.4 Informal conversations

In five of the six participating schools informal conversations (i.e. not part of timetabled meetings) about the curriculum and collaboration were reported between members of the science and mathematics departments. Most participating teachers also noted that they had not engaged in such conversations in other schools they had worked in. Three of the schools (Beebury, Ceeton and Eyston) had been built or rearranged to place the science and mathematics departments in close proximity, with common work space to encourage such conversations. In Effdon they were near each other but did not have any physical space in common. Ayford and Deecom were more typical secondary schools with departments not particularly near to each other and one staffroom for all staff.

At Beebury participants reported that science and mathematics staff were so used to talking to each other about the key stage three curriculum that they continued to do so about key stage four, even though they were not formally collaborating in teaching those students. At Ceeton, physics and mathematics teachers had collaborated over the teaching of mechanics at A-level, a topic common to both specifications, as a result of conversations in their faculty room.

It was at Eyston, however, where informal conversations were really the heart of the collaboration. The mathematics staff would tend to have coffee in the prep room at break with the science staff rather than going to the main staff room. ES and EM regularly discussed teaching and learning, sharing any difficulties that they were having and problem solving together. They were clearly breaking down the differences in discourse (Bernstein, 2000), which Frade *et al*. (2009) and Williams *et al*. (2016) identified as being a barrier to collaboration. These collaborative conversations had led to more formal collaboration and policy, but both clearly felt that it was in the talking and the conversation that they resolved the majority of the difficulties that they found. Both they and the headteacher suggested that this type of collaboration was easier and more likely in a small school – and in Eyston there are only four science teachers, three of whom are part time, and two mathematics teachers. It was also clear that EM and ES spent a considerable amount of time collaborating, with conversations happening in most breaks and lunchtimes.

6.2.5 Joint school trips

Ceeton had taken all of Year 8 to the Natural History Museum and had given them a trail round the museum which included some science-based and some mathematics-based questions. Deecom had taken all of Year 8 to the National Space Centre as part of their Year 8 Space project, with most mathematics and science staff going with them. Eyston had taken a joint trip to the Space Centre and were planning an environment day out to include calculating heights of trees using triangles and quadrat work with simple statistics.

6.2.6 The curriculum and scheme of work

In a sense it would be possible to say that all the projects were curriculum collaboration, but for this category I am taking collaboration in the curriculum to mean more broadly across the curriculum than in a one-week project. Beebury again takes curriculum collaboration further with their integrated teaching, as discussed in Section 6.2.2.

6.2.6.1 Eyston

At Eyston the curriculum and scheme of work collaborations have come about as a direct result of the informal conversations. EM and ES have produced a policy (see Appendix 15), included in their science and mathematics staff handbook, setting out the language which is be used across the two subjects. The participants gave the examples that mathematics teachers would continue to point out the different types of averages; science teachers would make clear that while there were different averages, the one used in science was the mean. They have agreed lists of names for equipment such as protractor not angle measurer, and have agreed a common policy as to how graphs are to be laid out. Both the head of science and mathematics felt that having this policy allowed them to save time in an overcrowded curriculum. The policy helps to further break down the differences in discourse, knowledge and practice identified by Williams *et al.* (2016). It does, however, reduce the freedom and agency which individual teachers have. An example was given of a science teacher who taught students to do graphs in a way that was not in accordance with the policy, although acceptable for external science examinations, and how they had to be brought into line. It would be much harder to bring teachers into line in a large school where there could easily be at least 12 teachers of each subject, teaching at greater distances from each other.

At Eyston they have also looked at the skills their pupils require in each year to ensure that if science requires quantitative skills that have not yet been taught in mathematics, science teachers are at least aware of it and know that they will have to teach those skills. The mathematics department will move their curriculum to aid science if they can, but they will not do so at the expense of what they feel is the best order for the mathematics curriculum. The language policy and science awareness of the mathematics curriculum is the type of collaboration encouraged by Boohan (2016).

6.2.6.2 Effdon

Understanding what is taught and when by each subject was also evident at Effdon. FS was well aware that there are mathematical skills required in science which not all students will have been taught. Understanding which skills they do have is made more difficult by students being in different groupings for mathematics and science and certain mathematics groups covering content far more slowly than others. For Effdon's science teachers it is the understanding of what students have and have not covered that is useful, allowing them to plan for the teaching in science of the skills that students will not yet have come across in mathematics. The need for teachers to understand each other's curricula – and particularly for science teachers to understand the order and timing of the mathematics curricula – was commented on by participants from other schools too.

6.2.7 Combined year 11 and 12 physics and mathematics lesson

At Ayford they ran a combined mathematics and physics lesson for year 12 students and invited interested year 11s to join them with the joint aims of encouraging the year 11s to consider taking the two subjects at A-level and to give all the students a look at some actual science and mathematics which was beyond the curriculum. The lesson was based on the press release from CERN when they thought they had data to show particles were travelling faster than light, but did not actually believe their own results (CERN, 2011). Students were shown a Panorama television programme about the dilemma. AM followed this with some input on a particular equation (the Lorentz transformation) and worked through a problem using it (if you have a five metre ladder over your shoulder and your garage is four metres long, how fast would you need to run so that your five metre ladder can fit inside your four metre garage) described by AM as 'wonderfully bizarre and counter-intuitive'. Students then worked in groups through some qualitative and quantitative examples of similar problems with AS. It was a very popular session, although described by AM as a huge amount of work to set up, largely undertaken by AS. They would like to do something similar again, but would not be able to use the same context in the following year as many of the same students could potentially be involved.

6.3 Summary

6.3.1 It can be done

From the descriptions of practice in these six schools it is possible to see that collaboration can and does happen between mathematics and science departments in spite of all the barriers documented by Venville *et al*. (2002) and others. Many of the identified barriers were in place in these six schools, but teachers in each of them had found ways to circumvent and scale the barriers, and they show that it can be done.

6.3.2 Response to external stimulus

In each school the collaboration had come about as the response to a different stimulus but in all the schools that stimulus was external to both the science and the mathematics departments. Bernstein argues that it is ‘crucial to know the source of the motivation to change’ (2000, p. 22). At Ayford, AM was asked to find a teacher of another STEM subject and develop a way of working together as part of the Cambridge STEM NRICH initiative. In Beebury the academy chain and the new building encouraged integrated teaching. At Ceeton it was having a new building designed to encourage collaboration and seeing what they could devise as a result. In Deecom there was external funding channelled through a deputy headteacher. In Eyston the departments were moved together by the headteacher to encourage conversations and, as the individual teachers involved got on well, this gambit worked. At Effdon the initial stimulus was a ‘mathematics across the curriculum’ workshop which led to a questionnaire and a response to the findings. In none of the schools had collaboration begun simply because a science and a mathematics teacher decided to work together. In some of the cases the collaboration was less a free choice by teachers than a result of coercion by those in authority. This is not to say that collaboration could not begin spontaneously elsewhere, but that it did not in any of these cases. I had originally intended to interview the head of science, head of mathematics and a senior leader from each school but it became apparent very quickly that they were often not the instigators, or the most involved, in the collaborations and indeed it was only in Eyston where these were the most appropriate people to participate.

6.3.3 Variety of styles

Each of the collaborations was unique as they had arisen as a result of a response to a different stimulus. Although most people when asked about collaboration tended to think of joint projects, several other types existed. While projects were the most commonly found style of collaboration, being found in four schools, no two of them were the same in content, structure, organisation or outcomes. Projects were not always popular with the teachers who had to enact them in the classroom, but the other collaboration styles (such as the visiting expert, language and graphing policy, conversations about curriculum and joint visits) show that it is possible for science and mathematics departments to work together without a joint project, and in ways which are both more popular and less time-consuming.

6.3.4 Finding connections

While authors such as Zhang *et al.* (2015) suggest that it should be relatively easy for teachers to find points of overlap in the content of mathematics and science, none of the participants had found making connections across the subjects straightforward. Suggesting it is relatively easy for teachers to find points of overlap presupposes that teachers are able to see connections between the disciplines, when to do so would require content knowledge of both subjects and an understanding of the connections both within and between them. Having the knowledge and appreciating the connections is recognised as being demanding and evidence of expert practice in just one of the subjects (Turner & Rowland, 2011); seeing connections across two disciplines when the teacher probably teaches in only one is clearly not as straightforward as many authors assume. This could been seen at Ayford where AM and AS had taken some minutes to recognise angles of incidence and reflection as an example of symmetry. At Ceeton, teachers feared being asked to find and make connections in front of a class as they were likely to find it challenging. That it will be challenging for teachers to identify meaningful connections between curricula when there is a strong departmental structure is predicted by Bernstein: ‘there will be weak relations between staff with respect to pedagogic discourse, as each is differently specialised’ (2000, p. 10).

In three of the four schools which had tried projects (Ayford, Beebury and Ceeton) the teachers had reservations about the science context of the project. In Ayford and Ceeton they clearly deemed their science contexts rather simplistic, and at Beebury they had included the same science context, healthy eating, a number of times over the two years of integrated teaching. Although the projects in Ayford, Ceeton and Deecom were in different science contexts and year groups, all of them were focused on data, statistics and graphing which, while undeniably important to science, is a fairly small proportion of the mathematics curriculum. Linked to difficulties with finding connections were concerns about rigour of the science and mathematics which could be covered in the joint projects, also identified as a teacher concern by Venville *et al*. (2002). Although the combined year 11 and 12 lesson at Ayford seems at first to be an exception to the difficulties finding rigorous connections, the lesson was specifically to take pupils into science and mathematics which was beyond the curriculum and the content covered was not part of the standard curriculum for either subject.

6.3.5 It can make curriculum sense

In spite of the difficulties with projects, collaborating with colleagues in other ways was highly valued by the teachers involved as making good curriculum sense. At Eyston, for example, EM and ES considered that their policy saved time in an over-crowded curriculum. A highly valued outcome of collaboration was improved understanding of the other department's curriculum, teaching and decision making.

6.3.6 It is fragile

Collaboration is often fragile. Four of the schools (Ayford, Beebury, Ceeton and Deecom) reported that there was less collaboration taking place at the time of my visit than there had been in the previous year. Thus even in schools which have managed to scale the barriers and begin to collaborate, that collaboration is fragile and at risk. When teachers have heavy workloads, the time taken to collaborate can become unsustainable. As projects were the most time consuming it is perhaps no coincidence that the schools where collaboration has reduced are those where they formed the major part of the collaboration.

In four of the schools there was a key person who was either the driving force behind the collaboration or who was the main person involved with organising it. In Ceeton and Deecom this person had left and, as a direct result, in Deecom the collaboration had stopped completely, and in Ceeton reduced considerably. This accords with Venville *et al*. who found that integration was reliant on 'local champions' (2002, p. 53).

6.3.7 Sets and groups

A key obstacle, mentioned in the three schools (Ayford, Ceeton and Deecom) where joint projects had been tried, was that of different groupings for science and mathematics. While this does not sound like a major issue, the way this barrier was overcome was significant for how teachers viewed the resulting project.

At Ayford, a project booklet set out what should be covered during each lesson sequentially. Teachers thus taught their own subject, but used what students had covered in the 'other' subject within their lessons. However, with students coming from several different groups, there were high demands on the teachers who had to deal with a huge variety in what students had actually achieved in the previous lesson in the sequence, even though they should all have covered the same material. These logistical difficulties were the main reason given for the project not being repeated as they had clearly caused a high degree of stress for the teachers and for AM and AS as project organisers.

In Ceeton, the project was longer and again teachers taught only their own subject. The lessons were not sequential, and each subject was more or less independent of what had been carried out in the other. This subject independence led to Ceeton's being the project with the fewest reported difficulties.

At Deecom they had tried two ways of coping with the grouping differences. Initially groups were rearranged to allow students to stay in the same class for the duration of the project, but this approach led to behaviour difficulties. The following year they left students in their usual classes, but each pupil had to work with someone who was in the same class as them for both science and mathematics.

Thus the way in which the barrier of different grouping was overcome had a significant impact on how teachers experienced the joint project. In general, the more freedom that teachers had to order their own classroom and teaching as they wished, the more content they were with the project. Beebury teachers were demotivated when the projects were specified too tightly and giving teachers more agency to organise their lessons in their own way was more successful. Likewise, EM and ES explained that not taking away teachers' freedom was a key reason to limit the collaboration at Eyston.

Collaboration, therefore, challenges the boundaries that Bernstein identifies between the subjects by changing the classification of the subjects. He argues that when such change happens there are:

> changes in organisational practices, changes in transmission practices […] changes in the concepts of the teacher, changes in the concepts of the pupils, changes in the concepts of knowledge itself. (Bernstein, 2000, p. 15)

These changes can be seen in the descriptions of collaboration in these six schools. For example, differences in setting and grouping in science and mathematics led to changes in how lessons were organised for projects. Giving students freedom to organise their own learning led to changes in transmission practices and changes in the concept of the teacher and pupils.

In Chapter 7 I will continue to use the lens of boundary to explore the data. I will also use the lenses of policy, transfer, and identity and beliefs to explore the relationship between science and mathematics in these collaborating schools.

Chapter 7
‘It’s a little bit frustrating’: the school findings examined through the theoretical lenses

In Chapter 6, I described the science/mathematics collaborations in each of the participating schools and identified seven different types of collaboration. I showed that mathematics and science departments could collaborate, that in each school collaboration arose due to factors external to the departments, and that collaboration was fragile. In this chapter I will examine the school data through the theoretical lenses outlined in Chapter 4, namely: power and boundaries; transfer; teacher identity and beliefs; and policy. When each lens is applied, different aspects of the data come into focus and, necessarily, fall out of focus. Using a range of lenses helps to establish a richer and more detailed picture of the relationship between school science and mathematics.

7.1 Power and boundaries

Boundaries, according to Bernstein (2000), are created and legitimised by power relations. I will show how using the lens of boundary helps to explain why collaboration between science and mathematics departments is challenging and why, crucially, it is unlikely ever to be genuinely mutually beneficial. In each school, initiating collaboration and, in the case of Beebury, reducing collaboration, is a change to established educational practice. Ball (1987) identified such changes as threats to vested interests as they can involve the redistribution of resources and changes in the way that information flows through the organisation. In consequence, changes in practice tend to enhance the position of some groups and disadvantage others.

Bernstein (2000) suggests that when classification (which he uses as a defining characteristic of relations between categories including subjects, as discussed in Section 4.1) changes from strong to weak or vice versa, as is the case with collaboration, we should always ask which group is responsible for initiating the change, whether they are dominant or dominated, and whose interests are served by such closer integration or relationship. Considering such questions will help to demonstrate how and why it is difficult for mathematics/science collaboration to be of similar benefit to both departments.

Using the lens of boundary and power I identify seven themes: 1) relationships across boundaries: blame and frustration; 2) language boundaries; 3) hierarchy and decision-making powers; 4) boundaries and asymmetry of dependency; 5) relationships across boundaries: the serving and the served; 6) physical boundaries; and, 7) cross-boundary communication. I will discuss each in turn.

7.1.1 Relationships across boundaries: blame and frustration

The relationship between colleagues across the boundaries of mathematics and science departments can be strained and characterised by blame and frustration. Mathematics teachers express frustration about the way in which school science uses mathematics; specifically, that the way it is used does not reinforce students' overall mathematical development. Science teachers express frustration that the mathematics curriculum does not support or underpin the science curriculum.

Mathematics teacher frustration at how school science uses mathematics is exemplified in this description of a science lesson observed by CML as head of faculty. CML could understand the emphasis the teacher placed on practical work and understanding science but, nevertheless, was frustrated at how, in what was to CML clearly a mathematical lesson, mathematical thinking was not promoted:

> *I was observing a* [science] *lesson last term, which was about bouncing. It was about losing energy, I think, and bouncing a ping pong ball and it was coming back up. And rather than talk to the students about what sort of data they were collecting and therefore what would be the best way of them representing that data and kind of getting them to think about it and perhaps not just jumping straight into it, they were told instantly what it was that they were going to draw 'and at the end of this, you are going to draw a graph and it's going to look like this.' And I just thought it was a missed opportunity for really kind of thinking about it* […]
>
> *'Why would you want to do this graph?'* […] *that discussion about why you're doing that and where that comes from, from the data, those discussions didn't tend to happen. I mean, there's an issue with time and practicals, obviously, but nonetheless, it's a little bit frustrating because you sit there thinking, well, there's some really good maths you could pull out of this.* [CML]

While CML could understand the science teacher's emphasis, there was clearly lingering frustration that the science teacher was not reinforcing learning that would take place in mathematics. CML suggested this missed opportunity was due to time and pressure to get a practical done – but in actual fact there is no requirement in the science curriculum to explain why a particular graph would be drawn either at key stage 3 or 4 (DfE, 2013f, 2015).

Frustration was also expressed by science teachers. For example, FS understood that the mathematics curriculum did not include or emphasise mathematics which would be important to science and was consequently frustrated by the content of the mathematics curriculum and the limited support it seemed to offer to the science curriculum. For example:

> *On the new* [science] *curriculum, they have to rearrange formulas on foundation papers, but yet they will never really do algebra* [in mathematics] *if they're a* [grade] *D or E or F student*. [FS]
>
> and:
>
> *I just feel quite frustrated by the maths GCSE; that it doesn't really seem to equip them appropriately. You'll get students who have got their* [grade] *B in maths and I teach them A-level and they cannot quickly work out numbers and they'll ask me how to do an average and little things that you're just doing all the time.* [FS]

Frustration about the differences and the lack of support the curricula offer to each other was expressed by teachers from five of the six schools. This frustration can lead to science teachers blaming mathematics teachers, with both the experience and anticipation of being blamed being described by mathematics teachers from three of the schools, exemplified by the following two comments.

Firstly, AM described a conversation intercepted in the staffroom:

> *A former colleague, science teacher, was sounding off about how awful it is that not everyone in Year 9 knows how to solve equations and it transpired that he was teaching some very, very weak pupils who could do some equations, but not the sort that he was wanting. When we had a conversation about how our scheme of work fits together and what sort of things they do at particular times, he realised that actually it was quite reasonable that they couldn't do what he was asking them to do.* [AM]

The teacher challenged by AM was apparently blaming the mathematics department in spite of not knowing about the mathematics curriculum and how it was organised into the scheme of work in that particular school. The science teacher appears to have been expecting too much mathematically of the pupils, both assuming they would have covered aspects of mathematics which actually they had not, and not understanding how difficult students might find solving that type of equation. These two problems (overly high expectations and not understanding how difficult pupils can find mathematics) were previously described by Dodd and Bone (1995) and more recently by Lyon (2016).

The experience of being blamed by science staff seems to be expected by some mathematics teachers. EM anticipates further blame for mathematics teachers in other schools following the changes to the science curriculum:

> *There's going to be a whole lot of blame going on with science departments saying they can't deliver their new course because the maths department haven't done their job properly and it's probably because they are not approaching it* [mathematics] *in the same way.* [EM]

EM was careful to state that the blame was likely to be experienced in schools where, unlike Eyston, there was limited collaboration between departments. EM here anticipates blame stemming from a difference in approach to the teaching of mathematics in the two departments.

As discussed in Chapter 6, collaboration between mathematics and science departments can lead to improved understanding of the mathematics curriculum for science teachers. Such understanding was a valued outcome of collaboration at Effdon and meant that FS, although frustrated by the difficulties students had with mathematics, did not blame the mathematics department for what students could not do: 'they're doing the job they're asked to do, but it doesn't really meet our requirements' [FS].

Thus it is apparent that frustration exists on both sides. To feel such frustration it is necessary to perceive colleagues as 'other', that is to see the other department as different and separate from one's own; to see the boundaries between them. Indeed, Newman suggests that 'The essence of a border is to separate the "self" from the "other"' (2003, p. 14). Mathematics teachers can be frustrated by how mathematics is treated in science; science teachers can be frustrated by students' difficulties in using mathematics in science. Both frustrations are made possible by the border. Consequently, mathematics teachers anticipate being blamed when students find it difficult to use mathematics within science, with this blame frequently stemming from the expectation that students will have covered the mathematics that they require for science during mathematics lessons and will be able to use it seamlessly in science. As mathematics teachers do not use knowledge and skills from science in the way that science uses mathematical skills, there is less expectation that what students have covered in science will support mathematics and consequently less blame.

FS, with a good understanding of the mathematics curriculum, was frustrated, but appreciated that it was the responsibility of science teachers to teach the mathematical skills required in science. Thus while understanding the curriculum of the other department does not necessarily lessen the frustration felt at the lack of support the subjects offer each other, it does appear to reduce the expression of blame.

7.1.2 Language boundaries

According to Bernstein, in order for there to be specialisation of any category, it is crucial to have a 'dislocation in the potential flow of discourse' (2000, p. 6). For him, 'A can only be A if it can separate itself from B' (*ibid*.) and part of that separation and insulation between categories is a break in the discourse, or silence between the categories. As a result, language can be expected to be distinct in mathematics and in science. Williams *et al*., although coming from a different theoretical perspective (that of cultural-historical activity theory), similarly argue that 'interdisciplinary work can be difficult, confronting […] differences in understandings of knowledge, discourse and practice' (2016, p. 6). In other words, there are acknowledged differences in how knowledge is understood, in how language is used and in the way mathematics is practised between mathematics itself and other disciplines which use mathematics. Redish and Kuo (2015) argue from linguistics research that the differences in how mathematics is used in university level mathematics and physics are so significant that they amount to different-but-related languages. In consequence, it should not be a surprise that significant differences were described in the way language was used in school mathematics and science. Many of the teachers who talked about the differences in language described their knowledge of these differences as being useful professional knowledge that was a direct outcome of their collaboration.

AM, in discussing how the differences in discourse had been overcome when working with AS, suggested, slightly tongue-in-cheek, that if there were no language differences then perhaps mathematics and science would be the same subject:

> *If* [language] *is exactly the same in maths and in science, if everything is the same in both, then it's probably just one subject and we probably shouldn't have science lessons, because we can do it all in maths. Or* vice versa*, but that's the sensible way round obviously.* [AM]

These language differences make it challenging for students to use mathematics in science, as ESL describes:

> *Mathematical language is part of the difficulty, I think, of children understanding mathematical skills* [in science]*. Sometimes they just don't understand the word you're using and when you demonstrate they say, 'Oh yes, I understand what you've got to do'.* [ESL]

For BS, understanding more about the mathematics curriculum and mathematics terminology helped to explain why students sometimes struggled with seemingly simple instructions given in science:

> *Apparently, you're meant to leave gaps between the bars if it's a bar chart but not if it's a histogram* […] *the kids, I'd tell them to draw a bar chart* [in science] *and they wouldn't understand what a bar chart was, because actually I was telling them to draw a histogram.* [BS]

Like the point made by ESL, above, BS highlights that students may be able to do the task they are being asked to do in science but the language used, and particularly the differences in language use between science and mathematics, acts as a barrier to student understanding. Both BS and ESL are suggesting that their students were able to do the task, and able to do it in the two different domains, but they needed help in negotiating the boundary.

Bernstein proposes that 'strong classification is likely to lead empirically to a dislocation in the transmission of knowledge' (2000, p. 11). Frade, Wimborne and Braga (2009) suggest that Bernstein's theories about boundaries can help to explain why it is difficult for students to transfer their knowledge across subject boundaries, with negotiating differences in how language is used being a significant aspect of the challenge. Many of the teachers talked about how their appreciation of language differences was relatively new; a key site of their learning about the differences was from informal conversations with colleagues from the other department.

Many of the specific examples of differences in language between mathematics and science given by participants were focused on graphs and graphing, probably at least in part because many of the collaborations were based on data collection and analysis. For example, FM describes a conversation with a friend who was a science teacher in the same school:

> [My friend asked me] *what do you call a line graph? And I was like, well, for me, a line graph is like a bar chart but you do this* [draws]*; she said for us a line graph is where you put little crosses and then you put a line and I was, no, it's a scatter graph, she went, no, no, it's a line graph, I was like, no, it's a scatter graph. So I mean, that just really tells you the problem, so you've got children who are being told in one subject this is one thing and in another subject, this is a completely different thing.* [FM]

The conversation reported between FM and the friend had obviously led to new knowledge of the science curriculum for FM. Through these conversations FM, an experienced teacher, was beginning to realise the implications for students who have to learn two separate meanings for a term in the two domains. Similarly, it was conversations which led FS to realise that mathematics and science were: 'using different language for the same activity'.

Participants also suggested a number of other terms which can have different meanings in mathematics and science including: the range, a single number in mathematics but two numbers separated by a dash in science; a line is always straight in mathematics but a 'line of best fit' can be a curve in science; the meaning of 'prism' is different in each subject. In geometry a prism is 'a solid figure with two end faces that are similar, equal, and parallel rectilinear figures, and whose sides are parallelograms or rectangles' (OED, n.d.), whereas in optics it is 'a transparent object in the form of a geometrical prism […] used for refracting light that passes through the sides' (*ibid*.).

7.1.2.1 Different degrees of precision

At Ayford, talking with AS had led AM to a realisation that there was variation in the precision required for certain terms between mathematics and science, including standard form:

> *In maths, our initial number is always between 1 and 10, whereas* [AS] *seemed quite happy to have 23 times 10 to the power of 7, whereas we would always turn that into 2.3 times 10 to the 8.* [AM]

Thus what would count as an acceptable answer for what is apparently the same task would vary between science and mathematics. 23×10^7 would be considered standard form in science, but in mathematics the initial number would have to be between 1 and 10 for the number to be considered standard form and thus 2.3×10^8 would be required. Many students would find it non-trivial to turn the answer from one form to the other and others may not appreciate the subtle distinction in what is required in the different subjects, or indeed why any distinction is needed.

The teachers thus recognised that differences in language are partly why students find it challenging to use mathematics in science. Although they were all experienced, the teachers in this study often talked about the discovery of language boundaries as being new to them, with the depth and breadth of answers about language variation across the disciplines varying widely. The teachers interviewed are unusual in that they do work closely with their colleagues in the other department; many reportedly gained their knowledge about language differences largely from their collaboration. From these findings, it would seem therefore that teachers of science and mathematics might, in general, have limited understanding of the differences in language, approach and emphasis that exist between the disciplines, and thus the challenge that students face in crossing the language boundary.

7.1.3 Hierarchy and decision-making powers

When classification weakens, as happens when mathematics and science departments collaborate, then Bernstein (2000) suggests that one should ask which group is responsible for initiating the change and whether they are dominating or dominated, in other words whether they come from the top or the bottom of the institution.

While most schools in England have a traditional department structure including heads of science and mathematics, it is conspicuous that three of the six collaborating schools had a different hierarchy. It is also noticeable that in none of the six schools was the collaboration initiated by discussions between the heads of science and mathematics.

Ayford, Deecom and Effdon have the traditional school structure with separate heads of science and mathematics departments. Beebury is arranged as three faculties, one being mathematics, science and technology (MST), which has been led by a science teacher since the school opened. Ceeton is organised in ‘zones’, with mathematics and science in the same zone, led by a mathematics teacher. While Eyston has a head of science and a head of mathematics, there is an over-arching science and mathematics faculty led by the head of science. In a study of collaborating schools in the early 1980s, Hart, Turner and Booth (1982) similarly found that collaboration was more likely when science and mathematics were in a faculty.

The decisions both to organise the school in a non-traditional way – in larger faculties rather than departments – and then which subjects to group together, were clearly taken at a senior level in the schools. In Beebury the decision to organise as faculties appeared to have come from beyond even the principal, from the academy chain and sponsors; at Ceeton and Eyston the decision came from the headteacher or senior leadership team. The impetus for collaboration in Beebury, Ceeton and Eyston likewise came from the headteacher or academy chain rather than from within the departments themselves and was linked to the decision to organise in faculties. Similarly in Deecom and Effdon, the impetus behind the collaboration came from the senior leadership team in the school rather than from individuals in the departments. To answer Bernstein's question, therefore, in each of these five schools the impetus for collaboration came from a dominating rather than a dominated group and from the top of the institution. Thus the collaborations, at least in five cases (Beebury, Ceeton, Deecom, Eyston and Effdon) were less a free choice by individual science and mathematics teachers than a result of compulsion by those in authority.

Ayford is a notable exception as the collaboration was initiated by AM who, as an Advanced Skills Teacher, was working outside the traditional department and school hierarchy. It was apparent during the interview with ATL that AM was highly respected and valued by the school leadership and consequently tended to be allowed significant freedom to experiment with different ways of working, with the collaboration with the science department forming part of that experimentation.

That collaboration was not, at least in any of these six cases, initiated by the heads of science and mathematics is perhaps not so surprising given Ball's (1987) observation that relations between heads of department are not always peaceful and can be fraught, with battles for resources and power. If a relationship is already fraught, it would be likely that innovations or changes in teaching practices, identified by Ball as tending to enhance certain groups over others, would be viewed with suspicion and resisted.

The question therefore arises as to why the impetus to collaborate came in five cases from those in authority. One interpretation is that teachers have minimal interest in working across departmental boundaries unless they are compelled, or at least strongly encouraged, to do so – making AM an unusual exception. It could instead be that the boundaries are so significant, the insulation, in Bernstein's (2000) terms, so strong, that it is extremely challenging for individual teachers to cross them, with research by Frade *et al.* (2009) showing that the boundaries are indeed difficult to cross. The data suggest that a high degree of support from senior leaders is required in order for collaboration to succeed, with the majority of participants suggesting senior leadership support as essential for collaboration. This interpretation is supported by Straw, MacLeod and Hart (2012) who found that senior leadership commitment was essential for interdisiplinary STEM activities to succeed. The need for senior leadership support in order to change the working practices of the school has been previously shown by Ball (1987). From this limited data set it is not possible to answer why the impetus was usually from higher up the school; further work in collaborating schools would be required to do so.

7.1.4 Boundaries and asymmetry of dependency

Bernstein (2000) suggests that when classification is weakened it is important to ask whose interests are served by the new togetherness. I will, therefore, consider how mathematics and science depend on each other and how this dependency correlates with the levels of benefit gained by each from collaboration. I will show how the dependency is unequal and asymmetric, and therefore, that the gains and benefits to the subjects likewise tend to be asymmetric.

A number of teachers noted how important mathematics and mathematical skills were to science, agreeing with Osborne (2011, 2014) who argues that two of the eight practices of science are mathematical in nature. Respondents suggested two separate reasons why mathematics was necessary for science students. Firstly that mathematics is key for future scientific careers (only an issue for those who choose such careers) and secondly that mathematics is required for all secondary science students to make progress in science, including those only just coping with the demands of the curriculum. FM gave a specific example of how learning aims in a science lesson were thwarted by students struggling with aspects of mathematics:

> *I was talking to a science teacher recently who was doing a lesson on Hooke's Law, which is where you put masses on a spring and then you measure the spring. And she went, 'So my learning intention was for them to learn that the stretch in the spring is proportional to the force that you act on it', but she said, 'right, okay, so the first challenge was none of them could measure the spring properly, because*

> *they weren't using the zero on the ruler. Then loads of them had issues drawing the axes on their graph and doing the scale properly, then plotting the graph, then drawing the line of best fit'. So she said '<u>my whole learning intention just got completely lost in all this numeracy and maths that they were struggling with'</u>.* [FM]

In just the one lesson students struggled with using a ruler, in particular with understanding that they need to measure from the zero, with choosing a scale for their graph, drawing axes using those scales, plotting the data, and drawing a line of best fit through the points. Lacking these skills, or at least struggling to apply them, was keeping students from the science learning that the teacher hoped for. In other words, the science learning was dependent on students' understanding and use of mathematical skills and thinking. It is easy to see why some science teachers feel frustrated when students struggle with mathematics, and how that frustration can lead to them blaming mathematics teachers for students' difficulties.

While a number of both science and mathematics teachers talked about how science was dependent on mathematics, mathematical skills and mathematical reasoning, none of the teachers talked about mathematics being dependent on science. Science was mentioned as a good context in which to do mathematics, and potentially a motivating context, but no one suggested that science was important to the mathematics curriculum or to students' chances of success in mathematics. Even when science was mentioned as an important context for mathematics it tended to be by science teachers who would like to see the mathematics department using scientific contexts to teach aspects of mathematics such as proportional reasoning or rearranging equations, and not by mathematics teachers themselves. Thus there is an asymmetry of dependency, with science dependent on mathematics but not *vice versa.*

This asymmetry of dependency is rarely, if at all, discussed in the education literature and yet it is critical in understanding the relationship between the disciplines. The asymmetry of dependency means that when science and mathematics work together more closely, when the classification weakens, there will tend to be greater benefits for science from such collaboration. This insight comes directly from asking, as Bernstein (2000) suggested, who benefits from the collaboration. Understanding the asymmetric dependency perhaps begins to explain the finding of Becker and Park (2011), who showed that, on average, effect sizes were larger for science than for mathematics following integrated teaching. If learning in science is dependent on mathematics, then a focus on mathematics in science will benefit students' learning in science. If learning in mathematics is not dependent on science then a focus on science in mathematics may not similarly benefit students' learning in mathematics.

Such a science focus in mathematics may, as authors including Becker and Park (2011) have pointed out, have a beneficial effect on students' motivation and engagement in mathematics – but the added engagement will not necessarily lead to improved understanding of mathematics. This asymmetry of dependency, and therefore of benefit, will make it very difficult for mathematics and science to work together in a way which is mutually beneficial, as called for by Osborne (2011).

7.1.5 Relationships across boundaries: the serving and the served

Unusually among the teachers interviewed, FML was not in favour of particularly close relations between mathematics and science departments in school. While this belief was unusual among those I interviewed, it should be remembered that the majority of interviewees were closely involved in collaborating and so FML's views may be more representative of many of those who teach mathematics. FML felt that mathematics was applicable more broadly than just to science and that emphasising the link to science risked diminishing those other links:

> *I think I'd really like to see collaboration across the curriculum more than saying maths is maths-and-science.* […] *I think it* [maths] *has far more areas it can be in than just maths-and-science and I would actually quite like to break down that image that, oh, it's maths-and-science, maths-and-science faculties.* [FML]

CML, in a school where mathematics and science are in the same faculty suggested that there were subjects it would be more interesting to be allied to: '*It's a real pity they didn't put maths with something like art* […] *it would have sparked off completely different things'* [CML]. In other words, two out of the six mathematics teachers interviewed – mathematics teachers who were collaborating with science teachers – did not particularly want or value a closer relationship with science. Given that mathematics is not dependent on science it is perhaps understandable that mathematics teachers would resist being tied too closely to science, but nevertheless the reluctance of a third of those mathematics teachers interviewed to work more closely with science suggests, at the very least, that it is not a high priority for mathematics departments, although the numbers in this sample are small. That science is not a high priority for mathematics educators and teachers was similarly noted by Orton and Roper (2000).

Several participants with a mathematics background raised the issue of mathematics as a 'service subject.' This is a term which carries within it the idea of being subservient and which is a topic of ongoing debate in the mathematics education community. The mathematician, astronomer and physicist Gauss (1777-1855) argued that 'Mathematics is the Queen of the sciences […] She often condescends to offer service to astronomy and other natural sciences, but under all circumstances the first place is her due' (quoted in Bell, 1951, p. 1). More recently, Hoyles, Newman and Noss identify the:

> tension that is present in mathematics itself, between the utilitarian pressure on mathematics as a service subject for other subjects, such as engineering or economics, and the requirements of mathematics as a discipline in its own right. (2001, p. 834)

And argue that:

> Mathematics has always had two faces. It is a tool in the study of the sciences, and it is an object of study in its own right. *(ibid*., p. 841)

This tension was present for some of the mathematics teachers who, while acknowledging that mathematics was important for science, were also keen to stress it as a separate subject as the following quotes exemplify:

> *I recognise maths as a separate subject, but that some of the things that maths will do are useful things to support science.* [AM]

> *I don't see maths as a service subject necessarily, because obviously I love maths and see that there's lots of beauty in what we're doing, but I do see that a lot of what we're doing is powering the science curriculum*. [EM]

FML pushed against the notion of mathematics being seen as too closely tied to science, in part not wanting mathematics in science to take priority over mathematics elsewhere: '*I don't want maths just to be seen as the prerogative of maths-and-science'* [FML].

In part this concern comes from acknowledging that there are other disciplines which are also linked to mathematics. FML in using the word 'prerogative' is also expressing disquiet over the increasing closeness of mathematics to science as this would suggest pre-eminence and therefore particular rights or privileges over the mathematics curriculum for science. Such concerns about the influence of science over the mathematics curriculum are also seen in the policy data set and will be discussed further in Chapter 8.

7.1.6 Physical boundaries

In part the boundaries between categories described by Bernstein (2000) are physical: each has differently specialised teaching spaces. Science, in particular, usually has specialised laboratories which mark the boundary of the territory of that department. Ball (1987) observed that departments fight each other for resources including access to and ownership of physical space. Furthermore, science departments frequently have a team-room which is generally only used by members of that department. This team-room can be a caring and supportive place and is a key site of collaborative learning within the department (Burn, Childs, & McNicholl, 2007), but when science staff spend the majority of their time within the department they do not get to know members of other departments, including the mathematics department. As Bernstein (2000) suggested, strong boundaries around departments will lead to weak relations and pedagogic discourse across the boundaries.

A key factor in cross-departmental collaboration mentioned by a number of participants, policy makers as well as school-based participants, was whether teachers even knew members of the other department. Mathematics and science departments in schools are often a long way apart. Indeed it was noted by the policy makers that teachers from different departments within the same school often only meet, or really talk to each other, for the first time at external professional development courses, particularly those which require a mathematics and a science teacher from the same school to work together.

It is notable that in four of these collaborating schools the departments are situated physically close to each other (Beebury, Ceeton, Eyston and Effdon). Physical proximity encourages informal conversations, which are at the heart of many of the collaborations, because at least the teachers in the different departments know each other. This proximity was recognised as being a factor: '*I think it helps that we're nearby*' [FS].

However, just being close by does not necessarily lead to collaboration or even better understanding. During the time when I was looking for collaborating schools which might be willing to be involved, I visited a school in London for another reason. As the mathematics department was next to the science department and they shared some teaching space, I asked if they collaborated and was told: '*No. They're annoying and they annoy us*'.

7.1.7 Cross-boundary communication

We have thus far seen that managing, or even beginning, communication across the departmental boundary is challenging. Yet despite this boundary, five modes of communication between staff across the departments could be determined from the data: 1) lesson observations; 2) joint meetings; 3) informal conversations; 4) via students; and, 5) facilitation by a key person.

7.1.7.1 Lesson observations

The lesson observations discussed were nearly all part of the schools' reporting and management structures and undertaken by more senior teachers. Those who had observed or been observed by a teacher from the 'other' department described it as useful in learning about the similarities and differences between the subjects. For example:

> *My performance reviewer is a science teacher and she came to see me teaching a lesson where I used a, what we use in maths as the data handling cycle* […] *My reviewer pointed out that, actually, this was very similar to the science investigation cycle*. [AM]

While a single lesson observation clearly only provides a snapshot of the other curriculum, for AM the resulting conversation had led directly to the collaboration with the science department being based around the data handling cycle and science investigations.

As a result of school power structures, lesson observations can be a one-way source of knowledge, though, as EM explains:

> [ES] *being my line manager as well, she will come in and observe maths lessons, and so she's very knowledgeable, probably more so about what goes on in my classroom than I am in hers, because I don't routinely get to go in and observe her lessons*. [EM]

7.1.7.2 Joint meetings

All joint meetings reported were for planning a project rather than talking about mathematics and science more generally, although there were plans at Effdon to invite some mathematics teachers into a science department meeting.

7.1.7.3 Informal conversations

Informal conversations took place between individual teachers or small groups from different departments. Such conversations were not in scheduled slots and often came out of a pre-existing relationship. For example:

> *One of my very good friends is the head of key stage 4 in science and we talk quite a bit about this* [mathematics-science]. [FM]

> *Having got to know each other* [...] *we then started having conversations*. [AM]

The participants who engaged in these types of conversations often had a broader awareness of the differences between mathematics and science. Many teachers pointed to these kinds of conversations as being the most useful in producing their knowledge of the differences. For example:

> *Working with teachers from another department can be quite eye-opening as well, as to how they work, how they plan, ideas they have. Even that short 2 or 3 minute discussion* […] *can be quite fruitful.* AS

Of all the descriptions of informal conversations, only one was between two people in a line-managed relationship (i.e., one was the manager of the other; EM and ES at Eyston) and they were described by the headteacher as being very good friends.

I would argue that it is the absence of power in these relationships which allows understanding to flourish in informal conversations. The absence of power reduces the boundaries which are, according to Bernstein (2000), created by power relations.

7.1.7.4 Via students

Some of the teachers noted students as a source of information about what they learn and how they learn it in other subjects. For example: '*We'd heard anecdotally from children things that they'd been expected to do in other subjects*' [FM].

However, other teachers acknowledged that students are not always the most reliable guide as to what they have been taught in other subjects, with student information no substitute for a teacher's own knowledge of the other curriculum. For example, ES suggests that their collaboration allows them to challenge students' claims:

> *When* [a student] *says, that's not how we were told to do it, we've then got the confidence to say, yes, it is, because we've discussed this and we know that you're told to do it this way in maths and it's the same as how you're told to do it in science.* [ES]

The need to trust in sometimes unreliable information from students demonstrates the lack of communication between the departments. Accepting such information at face value could also lead to science teachers blaming their mathematics colleagues for students' lack of understanding. It may well not be the intent of the student to deceive; however, it is possible that the difficulties in navigating between the two disciplines leads to student confusion.

7.1.7.5 Facilitation by a key person

In four of the schools there was a key person who facilitated the communication between departments. From Ayford, AM; Ceeton, the head of STEM (who had left); Deecom the deputy head (who had also left); and, in Effdon, FM, in charge of mathematics across the curriculum.

That this key person was essential for not only building but maintaining the lines of communication was seen in Ceeton and Deecom where both those key people had left. Those interviewed in each (and it was only one person in each school) noted that the departure of this person had reduced the commitment to and amount of collaboration between departments.

7.1.8 Summary

Thus while boundaries may not be physical, but rather socially produced, they are nonetheless difficult to cross (Frade *et al*., 2009). The most successful boundary crossing appears to result either from those in power compelling collaboration, or from informal conversation in largely power-free relationships.

Teachers, it would appear, often have limited knowledge of the 'other' curriculum and how it is structured, leading to frustration with the lack of support each curriculum subject offers to the other. Science is dependent on mathematics to a far greater degree than mathematics is dependent on science, which has two direct consequences. Firstly, the benefits from any collaboration will tend to be greater for science than mathematics. Secondly, teachers of science are more likely to be frustrated by students' difficulties with using mathematics in science and tend to blame mathematics teaching for these difficulties. Use in one subject of knowledge learned in another is known as transfer, and it is to the lens of transfer that I now turn.

7.2 Transfer

In this section, I will show how the lens of transfer can be used to consider students' use of mathematics in science and thus the relationship between mathematics and science. I will not explicitly consider students' use of science in mathematics as it was not a concern for any of the participants, although students making links between the two subjects was discussed by some. Transfer is a contested and controversial idea (as acknowledged by many authors including Frade *et al*., 2009) but is generally considered the use in one context of knowledge learned in another. It is of particular relevance to the relationship between school science and mathematics education due to the considerable body of research which demonstrates that students find it difficult to use mathematics in the context of science.

According to Osborne (2014), many science teachers operate with a vaccination model of mathematics, expecting students to be able to use what they have learnt in mathematics seamlessly within science and not considering teaching students the mathematics required to understand science as their responsibility. In spite of the prevalence of the vaccination model, he argues that supporting students to use mathematics in science is critical: 'Avoiding the opportunity to use mathematical forms and representations is a failure to build students' competency to make meaning in science' (2014, p. 187) and results in 'no deep understanding of science' (*ibid.*). AS similarly suggested that helping students understand the underlying mathematics can help them in understanding the science: '*Referring to mathematical techniques or ideas helps* [students] *understand the physics that we're doing*' [AS].

Improving students' use of mathematics within science has been suggested as a reason for collaboration (for example by Scott, 2012), while Honey *et al*. (2014) suggest making connections across subjects is often an implicit aim of collaboration. I will argue that transfer is not automatic, that teachers as well as students find it difficult to link the two subjects together, that transfer is often considered problematic when it does happen and that teachers can find it a challenge to support students in their use of mathematics within science.

7.2.1 Transfer is not automatic

Several of the teachers suggested that students will not necessarily see the links between the subjects, even when to teachers those links may be self-evident. For example, in describing the aspirations for what students might have gained from the collaborative work at Ayford, AM stated that:

> *I hope that they've seen that there are these links between the two subjects and that we do, for things like rearranging equations, we do that in maths, they do that in science, actually it's the same thing and whilst I think I'd previously seen this as blindingly obvious, that it's the same thing, I now think that pupils haven't and so I*

> *think that the sorts of collaborations that we've done I hope have started to open some eyes there*. [AM]

For AM, collaboration led to the realisation that students do not necessarily see the parallels between what they are asked to do in separate subjects; professional learning of this nature was a valued outcome of collaborating for many participants. EM suggested that part of the problem for students was realising when words in science *do* mean the same as they do in mathematics, when so often they do not:

> [It] *also means that* [students] *understand that when we're talking about vectors or acceleration or whatever, it's the same stuff that they're talking about in science, because I think often they think we don't mean the same thing. Because words don't, do they? 'Prism' in maths doesn't mean the same as in science.* [EM]

In other words, students who appreciate that there are differences in subject discourse may be inhibited from making links between the disciplines. This finding corresponds to Whitty, Rowe and Aggleton's (1994) conclusion that students who better appreciated the distinctions between subject discourses were inhibited from making links across the subject boundaries in oral work. Perhaps openly acknowledging and teaching about the differences between mathematics and science would help to remove these inhibitions. AM was unusual amongst the teachers interviewed in the focus placed on the differences between the disciplines as well as the similarities. According to AM, the Ayford project involved:

> *Highlighting the similarities and highlighting the differences between the two approaches, partly figuring that the similarities were important because there's no point learning one thing and then learning something else separately, when actually you can learn it once and then apply it in two situations* […] *but then also to make a big thing of the differences as well.* […] *They could see the starting point was the same in both, but that we then used them* [data and graphs] *in slightly different ways.* [AM]

Being able to highlight both differences and similarities would require teachers to have in-depth knowledge of both curricula. Knowledge of connections within just one discipline is seen as evidence of expert practice (Turner & Rowland, 2011); it is doubtful that many teachers have knowledge of connections within and across the sciences and mathematics.

A number of teachers suggested that students will often ‘claim’ not to know how to do something. ATL suggested that what students actually mean is that they have not learnt something in a particular context:

> *Pupils will come into technology lessons and you’ll ask them to measure something in millimetres and they’ll say ‘I don’t know how to’. And it transpires they have done this in maths, but they are thinking, ‘that’s what I do in that classroom’ and they don’t apply it in this classroom* […] *And sometimes it’s a challenge for us to remind pupils that things they learn in a workshop will also apply in a lab and also apply in a classroom.* [ATL]

For ATL, the challenge is for the teacher to know and understand what students have covered in the ‘other’ subject and therefore to help them to apply it in one’s own. Similarly, DS suggested that students need help to be able to see both the similarities and differences between mathematics and science, even within a joint project, and that such understanding is not spontaneous particularly where there are differences in terminology and disciplinary conventions:

> *Not just assuming that they’ll pick it up* […] *because in my experience, certainly the middle ability students really needed a hand to be able to say, ‘Oh look, the graphs are different’, or ‘Oh look, the terminology is different’*. [DS]

The difficulty that many students have in using their knowledge across the two subjects was evident even at Beebury. Although students have been taught interdisciplinary MST for two years, participants still reported that students find it difficult to transfer learning between the two subjects once they are taught separately:

> *Even though they get taught by their maths-and-science teacher* [...] *still, that transferability isn’t always there.* [BSL]

Teachers from several of the schools suggested that ‘more able’ children were more likely to use what they had learnt in one subject in another, although Porkess (2013) found that even students who are successful in mathematics can struggle to transfer their learning to other disciplines. However, the majority of students need help to be able to transfer their learning, to take what they have learnt in mathematics and to use it in science. This finding concurs with many other authors’ conclusions (for example: Dodd & Bone, 1995; Larsen-Freeman, 2013).

7.2.2 Transfer is problematic

When learning in one context impacts negatively on performance in another it is sometimes described as 'negative transfer' (Perkins & Salomon, 1992). Problematic or negative transfer was discussed fairly frequently by science teachers, but not reported by the mathematics teachers. The only instance which came close was a mathematics teacher complaining that prior teaching in science had spoilt an investigation the mathematics department wished to do to introduce a new topic. Almost always the negative transfer was due to differences in language and vocabulary – particularly when the same word means different things in the two subjects. FS gave an example which would have consequences for the marks students would achieve in a high stakes assessment:

> *So a range in maths, you take the lowest value from the highest value, but a range in science, you write the highest value, you write dash, then you write the lowest value, so on the ISA*[2] *paper they all wrote the range and I was like, 'no, no', and they were like, 'but Miss, that's what it is'.* [FS]

In this instance, transferring their learning from mathematics was having a negative impact on students' grades as what would be given credit when asked for the *range* varies between the subjects, even though both are in the context of data processing. Using the disciplinary conventions of the one subject in the other is not correct and students need to learn both and apply them correctly.

DS offered a similar example, where what students had been taught to write about graphs in mathematics impacted on their responses in high stakes science assessments:

> *The students have been drilled, I think, with some mathematical elements, so they are very quick to say 'positive correlation'* […] *and you know, whilst we talk about positive correlations particularly at A-level biology, it's not a phrase that we use with our exam board. Yes, they get marks for that, but if that's all they write to describe a graph, that's not enough detail.* [DS]

In science, students need to explain what the graph means and how it relates to the scientific phenomenon being graphed, rather than simply to recognise that it is mathematically a correlation (Wong, 2017).

[2] An ISA was a practical assessment marked in-school by teachers which formed part of the science GCSE

Thus participants here are offering evidence that transfer between the subjects does happen, but not always in the way that the teacher would like. Experience of being penalised for transferring between subjects where the disciplinary conventions, requirements or language are different, may inhibit students from transferring their learning in the future (as Whitty *et al*., 1994, showed was the case with oral work); perhaps beginning to explain why even students who have a good understanding of both disciplines do not always transfer their learning.

7.2.3 Teachers struggle to support transfer

Many authors acknowledge that there is a need for the teacher in the subject to which learning is transferred to help students to make the bridge between prior and new learning, although this idea is expressed in a variety of ways by authors from different theoretical perspectives. For example Rebello *et al.* (2005) argue that students need to be helped to 'reconstruct' their learning in the transfer context, where Larsen-Freeman (2013) explains this as the need to 'transform' learning in the new context. Schwartz *et al*. (2005) describe prior knowledge as 'preparation for future learning', arguing that students who have such prior knowledge will learn new knowledge more quickly, even if they cannot immediately recall it. Thus all these authors see a need for students to be helped to use prior learning. This need to help pupils to use learning from mathematics in science was acknowledged by many participants. For example, DS proposed that students only see links if they are helped to do so: '*Yes, if taught explicitly or explained explicitly, no for them just doing it on their own';* ATL suggested there was a need to remind students what they had covered elsewhere '*just by being explicit about it.*'

ATL continued by giving examples of where students could use knowledge from mathematics in technology but – critically – acknowledged that they would rarely do so spontaneously. Their knowledge from mathematics helped their learning in technology, in other words it was preparation for future learning as Schwartz *et al.* (2005) argued, but it was not spontaneously transferred.

Wood concurs that students can require help in using existing knowledge in a new situation, and that such help and prompts can mean the difference between success and failure:

> Children may know how to solve a problem, in the sense that they have the resources to solve it, but they do not make use of those resources spontaneously […] Even minimal prompts from another person, when these are contingent upon

> the child's activity, can motivate children to think and to succeed where, left to their own devices, they act impulsively and, in so doing, fail to mobilize their resources to tackle problems that they are capable of solving. (1998, p. 269)

ES agreed that the majority of students would not be able to use mathematics in science spontaneously, but that they could if they were reminded what they had covered previously:

> *I know they've been taught it and taught it well but they probably might not remember it because it's been a while and so* [we] *would just have a quick recap for 10 minutes to go over that* [mathematics] *first. Again, knowing how they've done it, to be able to say, this is what your maths teacher told you, we're going to use that in science, just a quick reminder, this is what you do.* [ES]

ES is describing what Rebello *et al.* (2005) call reconstructing learning in a new context. The reconstructing is apparently simple – a few minutes recap of the prior mathematics learning – but to do it effectively ES needs to know what students covered in mathematics, when and how. At Eyston, they suggested one of the key reasons to collaborate was to save time in an overcrowded curriculum. Yet they do not expect students to transfer their learning without being supported to do so; saving time does not mean never needing to refer to mathematics in a science lesson or expecting mathematics to act as a vaccination, as described by Osborne (2014).

Even among these teachers who were collaborating there was acknowledgement that they did not know as much as they would like or perhaps needed to about the 'other' curriculum. Wanting to know more about the 'other' curriculum was almost always articulated by science teachers who felt that they needed to know more about the mathematics curriculum. While mathematics teachers were no more informed about the science curriculum, it was never expressed that such a lack of knowledge might be a problem for teaching mathematics. For example, AS suggested that not knowing the mathematics curriculum limits what can be done in the classroom to support students' use of mathematics:

> *I would like to know more about their curriculum so I would be in a better position to be referring to maths in my science lessons*. [AS]

DS suggested that finding out what is in the mathematics curriculum and adapting the science curriculum accordingly would not be particularly difficult, but this had been systematically done only at Beebury and Eyston, although there were signs that it was starting at Effdon.

> *I don't think I know enough about what they teach and when* […] *and that, thinking aloud, is not a particularly complicated thing to do, to ask them for a list of what they do and we look in science at what they teach and when and we try and, you know, tie our curriculum in a bit better with theirs*. [DS]

For FS, collaborating helped to highlight that there was a problem, which was the start of looking for a solution: *'We realised that we were teaching things in science that they hadn't encountered in maths at all'* [FS]. It is important to realise that FS had been teaching for several years, and was a head of department when this collaboration began, further suggesting that knowledge of the mathematics curriculum is relatively rare among science teachers.

A number of teachers also pointed to a lack of knowledge of the 'other' pedagogy: of science teachers not knowing how topics were taught in mathematics and mathematics teachers not knowing how mathematical skills were used in science, as these quotes exemplify:

> *I think a lot of science teachers don't know <u>how</u> maths is taught by the maths department. Their experience is how they were taught at school, which is not the same.* [EM]

> *The bit we're still struggling with is <u>how</u> do they teach it?* [FS]

Two related problems are thus identifiable – firstly science teachers knowing whether or not students had encountered the mathematics that the science teachers expected, and secondly what the science and mathematics departments might do when students had not covered mathematics when they needed it in science.

There were two suggested possible solutions where there was a mismatch: mathematics could alter the order in which they teach some topics or science could teach the mathematics they require themselves. Reordering the curriculum was not seen as a simple option. Mathematics, after all, links with many subjects and not just to science. However, there was willingness in some mathematics departments to consider reordering the curriculum, for example:

> *We're looking at whether we can rejig our maths curriculum, the order that we do things in maths, and not do it quite in isolation*. [FML]

This approach could potentially become complicated, however, given the number of different departments in a school, all with varying needs. Even at Eyston where mathematics teachers were only trying to accommodate science, it was acknowledged that it would not always be possible to reorder the mathematics curriculum to suit science:

> *We both had the premise that I had my* [maths] *curriculum to teach and* [ES] *had* [the science] *curriculum to teach and I wasn't going to move things about that were going to cause us a problem. If it was easy to move things and therefore just change a sequence within a year which made things easier for them then I would do it, but if it wasn't possible because there were too many things that were based on it, then* [ES] *would undertake* [to] *teach that bit directly*. [EM]

FS at Effdon likewise took the line that they could teach aspects of mathematics that were needed within science, but that it was necessary to first find out what mathematics students did not know:

> *Finding out what our children don't know, and allowing time when we teach certain science topics* [for students] *to learn how to do graphs and scaling and lines of best fit*. [FS]

In other words, they would find out what students had not covered in mathematics and then build time into their own curriculum to cover aspects of mathematics where necessary. This is the type of planning required when the vaccination model (as described by Osborne, 2014) is not adhered to.

The picture is further complicated in that, in many schools, students are set differently in mathematics to how they are set in science and other subjects. In some schools setting policies are different in each department, for example at Deecom there is a wider range of prior attainment in science classes and more finely grained setting in mathematics. In other schools setting policies are similar, but high attainment in science does not necessarily mean high attainment in mathematics, and *vice versa.* As not all mathematics teachers will teach the same way and not all teachers will even teach all their classes in the same way, science teachers are searching for a chimera if they are looking for 'the' way that their students are taught a piece of mathematics, a point acknowledged by FM:

Part of the problem is that even as a maths department we don't do things the same way. The way you would teach certain things to one set is different to how you would teach it with another set and then they go in their mixed ability group to geography and they've been taught four different methods. [FM]

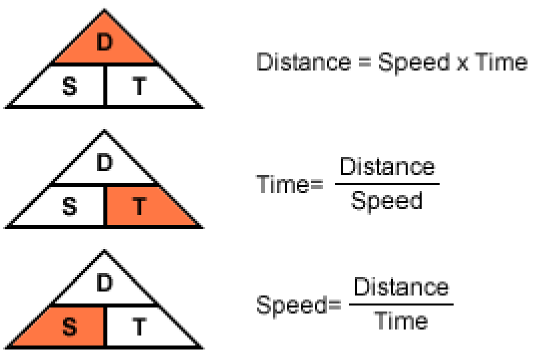
No one suggested any answers to this problem, although it was acknowledged as difficult:

The disparity between other subjects teaching mixed ability and having a whole mix and students not having met it, and it wouldn't be appropriate for them to meet, is one I haven't got the answer to yet. [FML]

Helping students to transfer their learning and reconstruct it in science thus requires teachers to have knowledge of the mathematics curriculum including when and how various topics are taught. Knowledge of the connections across the curriculum in just one discipline is evidence of expert practice (Turner & Rowland, 2011). Given that the participants in this study were all experienced teachers and described much of their knowledge of the 'other' curriculum and pedagogy as coming from their collaboration suggests, at least, that knowledge of connections across mathematics and the sciences is rare and thus the majority of science teachers would struggle to support students in reconstructing mathematics learning within science.

7.2.4 Transfer and triangles

When science departments do teach the mathematics themselves, the way they do it would not always be approved of by the mathematics department. The triangle method for rearranging three-part equations of the type *a = b x c* was mentioned by teachers from five of the six schools, frequently as an example of difference in approach to mathematical topics. The triangle method is the following:



This method is relatively common in many science departments and less frequently used in mathematics, although it does appear to be becoming more popular, being used, for example, on the BBC Bitesize mathematics revision web pages (BBC, 2017). Many mathematics teachers dislike the use of triangles, arguing that using them does not require an understanding of what is going on when an equation is rearranged:

> *You're not using any maths at all when you're using that triangle, you don't understand what you're doing at all, it's just magic, it's a magical thing.* [FM]

CML did not like them either, but recognised that they were used in science due to the different priorities the subjects had in their lessons:

> *Science's focus is on getting a practical finished and therefore, they're going to use a trick to get them there and if it means* […] *using the triangle, they'll do that, so I think it's because we've got different priorities.* [CML]

Some of the science teachers realised that the triangles were not used by mathematics teachers, for example DS: *'They* [mathematics teachers] *don't seem to use the triangles that we often use for rearranging equations'.* However, although triangles were regarded as 'magic' and 'a trick' by some, not all mathematics teachers regarded them entirely negatively. AM talked about using triangles and recognised that their department did so as students were comfortable with them from science. This is an unusual example of the mathematics department effectively borrowing, or grudgingly accepting, pedagogy from science, and may also be an example of (perhaps unwanted) transfer from science to mathematics.

> *We make use of formula triangles because they're familiar with those in science* […] *and you know that pupils know how to use those, so we use them in maths as well, we borrow those.* [AM]

Even FM, who was generally scathing about triangles, did admit that they can be beneficial and were used by one of the mathematics team to allow students to access part of the curriculum where they would otherwise struggle:

> *There's even somebody in the maths department who does* [triangles] *with trigonometry* […] *she did that with trigonometry to a group that wouldn't otherwise be taught trigonometry.* [FM].

In other words, triangles can be useful to make aspects of the curriculum more accessible to students who would otherwise struggle. Some of the participants suggested that the mathematics required in science is harder than that required in mathematics, as exemplified by the following quote:

> *Sometimes I feel the skills they're being asked to do in physics are much harder than the same skills that we're trying to teach in maths*. [EM]

Thus triangles may be being used in science to help students to access aspects of the curriculum which they find challenging.

The use of triangles can potentially be an example of procedural teaching of mathematics skills, with Southall (2016) suggesting such procedural teaching bypasses understanding and reduces students' confidence in whether their answers are likely to be correct. Mathematics educators Boaler and Greeno (2000) argue that procedural teaching requires students to surrender their agency and can lead to capable students rejecting such subjects, which they perceive as not requiring them to think. Boaler (2002) also links procedural teaching to transfer difficulties, suggesting that transfer is less likely to happen when students are taught to follow procedures, rather than to think for themselves.

7.2.5 Summary

Transfer between science and mathematics, expected by many science teachers to be unproblematic (Osborne, 2011, 2014), is challenging for the majority of students and they need help to use mathematics within the context of science. It can be difficult for science teachers to help students to use mathematics for a number of reasons: they may not appreciate how demanding some students find mathematics; they may be frustrated by negative transfer, particularly if they do not know about the differences in language between the domains; they may not realise that students have not covered in mathematics what they anticipate; they may not have knowledge of the connections across science and mathematics. Mathematics teachers can be frustrated with how science teachers deal with the mathematics in their curriculum, considering that they use 'tricks' to avoid mathematical thinking, although some are borrowing triangles from science to help students access mathematics they may not otherwise understand.

7.3 Identity and beliefs

That teacher identity and beliefs affect curriculum decision-making was discussed in Chapter 4. I have already shown that teachers may struggle with knowledge of connections across the curriculum. In this section I will argue that collaboration may force teachers to confront aspects of the curriculum where they have less knowledge, potentially challenging their identity both as a 'subject teacher' and a 'good teacher.'

7.3.1 Teacher beliefs and philosophy

Teachers can have deeply held, although unexpressed, beliefs about teaching. Wallace (2014) argues that teachers filter curriculum innovations to see whether they resonate with those core beliefs and can find it hard when asked to teach in a way that they do not believe in. To change teachers' practice requires both cognitive and enactive mastery experiences (Glackin, 2016).

It was at Beebury, where the curriculum is fully integrated for Years 7 and 8, that the need for teachers to believe in integrated teaching was most clearly expressed: '*It works most successfully when you've got buy-in and you've got that mind-set of this pluralistic style of teaching'* [BT]. 'Buy-in' and 'mind-set' is about more than feeling confident in the different subjects, it is about teachers believing in what they are delivering. BT suggests that unless teachers have that belief it can be very difficult to support them to change their teaching style. Understanding integrated teaching (cognitive mastery) and seeing how it can work well (enactive mastery) can help teachers to change their thinking and thus their practice, but BT acknowledged that this can be very time-consuming.

Beliefs have an impact on the choices that teachers make in the classroom and what they are confident doing in a classroom. Beebury has the most integration or collaboration of any of the six schools and so it is here where there is the greatest challenge to beliefs and identity. There are echoes of the potential challenge collaboration can pose to teacher beliefs in other interviews though, underlining that what people believe in influences the way that they choose to teach. For example, at Deecom:

> *I think your heart has to be in cross-curricular teaching, because it is not normal lesson objectives* […] *I think the danger was that if teachers weren't fully engaged, the experience was worse than conventional lessons.* [DS]

In other words if teachers' hearts are not in what they are doing, if they do not believe in it, then they will not produce the best lessons. If science teachers fundamentally believe that collaborating with mathematics (or *vice versa*) is not part of their role, or not a productive use of time, then it is going to be very difficult to encourage them to do so. Conversely, collaborating is something AM does believe in: '*This* [collaboration] *is stuff that I'm doing because I think it's worth doing*'.

At Beebury they were reducing the amount of integrated teaching and it was evident that doing so was difficult for some of the teachers as they believed so passionately that it was in the best interests of the students:

> *I almost think what we're doing at the moment is to protect what we believe in* […] *Give up some bits of it, so that we can maintain that project based learning, wider commitment to education, but it's quite a depressing conversation*. [BS]

For these teachers, the prospect of the curriculum being arranged in a way which does not match what they passionately believe in is a cause of stress and anxiety.

DS believes that it is the duty of all teachers to teach mathematics in their lessons as appropriate:

> *Well, this idea that maths is taught by the maths department, literacy is taught by the English department is, surely no-one subscribes to that anymore. So I think we all, all of us have a duty to deal with maths and literacy, and IT of course, in any lessons that it's appropriate*. [DS]

One belief many of the teachers shared was for equity of access for all students, including to the opportunities which were offered by their collaborative teaching. For a number of teachers, the opt-in/opt-out nature of most STEM activities in schools was problematic, particularly where STEM is limited to the STEM club and those children who choose to attend. Yeomans (2017) even argues that science or STEM clubs can be perceived as unwelcoming to students from certain groups in society and add to inequity of access to science. For the participants, working through the curriculum and through projects which were for all chimed with their beliefs in equity as it ensured that all students participated.

> *The exciting thing for me was that they didn't have a choice, it wasn't an opt-in or opt-out thing, it wasn't just for a limited number of pupils* […] *every pupil in Year 9 did it, so there's no opting out, this was for everyone.* [AM]

Teachers were very clear that they were interested in collaborating between mathematics and science because it would benefit all pupils, not only those who might choose to participate and perhaps go on to further academic study. This finding may help to explain why the national STEM policies struggled to gain traction in schools (NFER, 2011). I previously demonstrated (Wong *et al*., 2016) that national STEM initiatives in England were strongly focused on those already identified as high achievers; such a focus would not sit comfortably with teachers' beliefs in equity of access.

7.3.2 Subject loyalty and identity

Love of, and loyalty to, the subject were mentioned by some participants as reasons why teachers might be reluctant to teach in a collaborative way when it would involve teaching outside their specialism. For example*: I think as a secondary school teacher people almost sign up to promote their area and their passion for their area* [BT].

Siskin (1994) similarly showed that teachers' identity is anchored in their subject. In consequence requiring them to teach another subject challenges teachers' identity as a subject teacher, as a mathematics teacher, a science teacher or a specific science teacher such as a chemistry teacher. BT even suggested that asking teachers to teach outside their specialism can lead them to feeling they are betraying their original subject and they can as a result lose their passion for teaching:

> *Teaching out of specialism* […] *I think at times* [teachers] *almost feel like they're betraying what their knowledge or belief is*. [BT]

BS agreed, suggesting that this was particularly problematic for science teachers. At the start of their integration, BS reported that many of the staff had argued that*: '"I am a science teacher, why should I teach maths?"'* [BS]. Being required to teach out of specialism therefore challenged their identity as a science teacher or subject teacher.

7.3.4 Confidence and identity

CML noted that teacher confidence is likely to be higher within their own subject: '*I think we have that confidence within our own subjects, but not necessarily with the other one'* CML. However, some teachers may lack confidence, not just with the 'other' subject but also within their own. If teachers are less confident they are less likely to be willing to take risks, including risking getting an answer wrong in front of a class or colleagues. Thus lack of confidence could lead to teachers avoiding collaboration with colleagues where they could be put on the spot or shown up as lacking knowledge.

Fear of mathematics is well-documented and it was reported as being present among science staff as well as teachers of other subjects, according to some of the participants: '*Maths phobia I think* [is] *equally as prevalent in schools amongst staff as it is out in the wide world'* [FML]. Some interviewees also noted that science teachers may not be as numerate as may be expected: '*You don't always get very numerate* […] *science teachers'* [BSL].

CML was also surprised to find this fear and lack of mathematical confidence among science staff:

> *I think it's bizarre to say, but even science teachers are scared of doing maths, is part of the problem* […] *I find that surprising because you'd imagine in a science degree, they've done an enormous amount of maths* […] *it would be nice for them to feel much more confident about being able to deliver it.* [CML]

Although science teachers not always being very confident with mathematics came as a surprise to some of these participants, lack of confidence with mathematics in the wider population, including science graduates, has been described previously, for example in the very influential Cockcroft report (1982). Lack of confidence with mathematics is likely to become more of an issue for science teachers due to the increase in the mathematical content of the science curriculum.

In most schools it would not be a problem were the mathematics teachers to lack confidence in science; Beebury with its integrated curriculum is an exception. BSL pointed out that science contains a lot of subject specific information which can make it hard for mathematicians to teach science. In their integrated curriculum they notice that teachers put their own subject specific slant on whatever they happen to be teaching. For example:

> *I went and saw a maths teacher teaching genetics and the probability aspects of it were absolutely brilliant, did a great job on it, but the biological aspects of it, left a lot to be desired, you know, the sort of DNA structure and the rest of it. So I think it gets a skew towards the subject specialism*. [BSL]

Those joint projects which required teachers to teach out of specialism in other schools could present similar challenges to those at Beebury. For example:

> *In science, if a student was trying to teach themselves about luminous and non-luminous objects* […] *or, I don't know, moon shadow,* [science teachers] *would find it very easy to go to the prep room and grab the resources, you know, a torch and a ball and a larger ball, and I guess the level of maths that we were asking them to do was within the comfort zones of the vast, vast majority of my science teachers. I'm not sure the same is true of the maths department, if a child turned up there and*

said, can you help me understand how, they didn't have the equipment and I think sometimes the knowledge, so I think probably it was a little easier for us, but it was our project to start with and we were asking them to help, so if it had been fractions, you know, whatever, it would have been the other way around. [DS]

Thus DS acknowledged that teachers of the subject on which the project was based would have the easier time teaching any joint lessons. Deecom's project was science-based and thus easier for science teachers. However, integrated projects are often science-focused (Pang & Good, 2000), suggesting that the challenge is often greater for mathematics than science teachers, particularly as many mathematics teachers will not have a background in science. Indeed, of the mathematics teachers I interviewed, three had first degrees in, respectively, law, economics and philosophy and thus may not have studied any science at all beyond GCSE. It is also, of course, possible that those with first degrees in mathematics may not have studied science beyond GCSE. Indeed, the Principal of Beebury admitted that it may be more difficult for mathematics teachers:

I'm more likely to say that science teachers are better at handling the maths, than maths teachers handling the science, because there's a lot of subject knowledge there […] *but I would never say that in front of the team*. [BSL]

BSL similarly argued that requiring people to teach a wide range of subjects would be to put them into a position where they are bound to be less competent:

I think there's a spectrum where people can teach and teach competently and then there's a wider spectrum where they can teach, but it's going to be stretching it if they're going to be competent. Then there's a wider spectrum where they're going to be incompetent because they can't possibly have the skills, knowledge and understanding at a certain level where they can do it. I fundamentally believe that good teachers can be good teachers of anything, but you need to put a lot of effort into making sure they can do that, real CPD. [BSL]

Teachers' lack of confidence to teach outside their own subject area may, therefore, be for very good reasons. Carlone and Johnson (2007) argue that identity includes competence, performance and recognition. Thus classroom activities which a teacher feels they cannot perform competently, as they are less confident with the subject matter, will challenge their identity as a 'good teacher.' There can be further challenge to the 'good teacher' identity if it is also recognised by others, be that students or staff, that they are less than competent in an aspect of classroom practice.

Additionally, Boaler (2002) has argued that for students to use mathematics successfully outside the mathematics classroom, they need to develop a productive relationship with the subject. Such a relationship will develop, at least in part, through feelings of confidence in relation to mathematics. The same will also be true for teachers. If they do not have a productive relationship with mathematics developed through confidence and positive past experiences – and the quotes above suggest that for many science teachers this may be the case – then they are not going to look for ways to bring mathematics into the classroom, they are more likely to avoid doing so as much as they can.

Even AM, who liked working across departments, admitted that it was easier to stay within the comfort zone of mathematics:

> *I, as a mathematician, can stay in the maths world and I can do maths, but I can go into 10 minutes of one of* [AS's] *lessons and I can do a maths bit that's relevant* […] *the visiting expert bit means that I don't need to do science-y things, I could do maths-y things* […] *but we can still work together, which is why I think that's such a good model.* [AM]

The projects and collaborations which appeared to be more popular with the staff, and therefore more enduring, were those which allowed teachers to stay within their own world, while still interacting with teachers from other departments. Such approaches allow teachers to remain where they feel confident and also provide less challenge to their identities both as a 'good teacher' and as a 'subject teacher'.

7.4 Policy

National policy sets the context in which schools operate as it is the means by which government seeks to influence what happens in schools, classrooms and even individual lessons. It is enacted in different ways in different schools and can have consequences unintended by the policy makers (Maguire, Ball, & Braun, 2012). In this section, I will consider the curriculum, assessment and examinations, Ofsted and the STEM agenda as they appear to impact upon collaboration between mathematics and science departments in schools.

7.4.1 National Curriculum

Among the teachers who had knowledge of the 'other' curriculum there was frustration with the lack of linkages across subjects or across key stages in the national curriculum. Teachers commented that this mismatch made it difficult to plan work across key stages and contributed to difficulties in working together across departments. For example:

> *I don't think there's any down sides about collaborating. I feel you just hit a brick wall at points because they're just disparate, they're just the science curriculum and the maths curriculum, I don't know if they ever spoke when they were writing those two*. [FS]

EM similarly questioned how the curricula were written and pointed to the lack of an overarching view of how the curriculum fitted together:

> *I think it's something nationally, that the people who write the maths and the science* […] *they need to have done that* [thought about the order] *and they haven't and it seems really stupid to me that they've put things in Year 7 and Year 8* [science] *that won't come up in maths until much later. There's no joined up thinking, is there?* […] *And you think surely there must be somebody who could have an overarching view of those two subjects and see how all the skills fit together, but everyone's very precious about their own subject* […] *It's silly. I think the next time they redo the curriculum, it should be maths and science together and have like a maths side and a science side and do it like that*. [EM]

FML raised the issue of mismatch in expectations across subjects and suggested this was a wider problem than just between science and mathematics:

> *It was also interesting because I think when national curriculum and schemes of work came out* […] *nobody sat down and linked what we were asking a child to do in Years 7 or 8 in geography, in science, in English, in maths, there's just a total mismatch. So you find that students were coming in, say, at a particular national curriculum level in maths, they were, say, level four, but in geography, they might be being expected to do maths that was level six or seven and there's this huge mismatch*. [FML]

And across several key stages:

> *Let's hope though that this time they've actually linked key stage 2 and key stage 3 and key stage 4 and actually talk to each other, because they didn't last time*. [FML]

The impression that these teachers have is that there was no communication across key stages within subjects, or across subjects within key stages, when the national curriculum was written. The way the curriculum is structured has impacts within schools, including on relations between departments, and will be followed up in exploring the interviews with the policy makers in the next chapter.

When the school interviews were carried out, all the teachers knew that a change to the curriculum was coming. In the earlier interviews it was not yet clear what the new curriculum would look like, with more details available with each successive school visited. At some of the later interviews it was noted that collaboration would be a much lower priority than understanding their own new curriculum. For example: *'I don't think anything will be done* [collaboratively] *in advance of the spec change because we'll be too busy'* [DS].

Changes to the curriculum will also exacerbate one of the other key barriers mentioned by many teachers – the lack of knowledge of the content of the other curriculum:

> *I haven't even got my head round what's happening in other subjects, because we're just about getting our head around what's happening in maths.* [FML]

Understanding the content and structure of the other curriculum will clearly be made more difficult during and following changes to the curriculum, particularly as in the GCSE changes that schools were planning for, key stage 4 mathematics and science changed in different years, meaning that the match-up between the subjects at GCSE was substantively different for three successive years.

7.4.2 Ofsted

That Ofsted priorities, or at least perceived Ofsted priorities, affect school priorities was acknowledged by many of the teachers. Similarly, in a study on policy enactment in secondary schools, Perryman, Maguire, Braun and Ball found that schools were 'prioritising policies according to the perceived (and ever-changing) Ofsted agenda' (2017, p. 17). Ofsted was mentioned by staff at three of the schools (Beebury, Deecom and Effdon) as a limitation to collaborative working; Eyston, being independent, was not subject to Ofsted inspections in the same way. At Deecom, where the previous collaboration had ceased, Ofsted was mentioned as part of the reason for the shifting of priorities to no longer include collaborative working. Beebury had been very recently inspected when I visited and the outcome of that had reinforced the principal's decision to reduce the amount of integrated teaching. Effdon had been inspected the term before I visited and had come out well. However, two of the three teachers commented that the inspection's focus on literacy made it harder for them to get the traction they needed to work on numeracy. FML also commented that school leadership teams are very sensitive to the messages that are given out by Ofsted:

> [Ofsted] *did a literacy walk, they did not do a numeracy walk.* [It] *sends out a very strong message to leadership teams and, you know, leadership teams at their peril ignore those messages*. [FML]

Effdon is not unusual in listening carefully to the messages from Ofsted. Perryman *et al*. (2017) argue that part of Ofsted's role is to educate teachers and school management about what constitutes successful school practice, leading to schools changing their practice to conform to what they think the inspectors require:

> Not only are pupils being educated in certain regimes, but the teachers and management of the school need to be 'educated' into accepted modes of successful practice. Inspection plays a key supervisory role in this discipline and sets the agenda by which successful practice is measured. (Perryman *et al*., 2017, p. 3)

They similarly demonstrate that 'the leadership teams in our schools identified many of their policy priorities according to Ofsted requirements' *(ibid*. p. 10).

Like FML, FS felt that there was far greater support for literacy than numeracy from Ofsted, which had a direct impact on resulting school priorities:

> *I think Ofsted placed a really big push on literacy and that then forced the school to put a really big emphasis on literacy* [...] *so there's this massive investment of time and resource to do it, but I don't feel the same has happened for numeracy*. [FS]

FS, having seen what had happened with literacy, also commented that Ofsted could be used to drive a government policy of more numeracy across the school. FS suggested that this might be a better way to go about doing so than to significantly increase the amount of mathematics in other qualifications, including science:

> *I think if something becomes a major Ofsted priority then the school prioritises it and spends money on it and I think if the government are really serious about*

> *numeracy, I don't think the best way to do it is just ramp up what's in our exams, it's probably to say, you know, your school's grading will be judged on how well you're implementing it*. [FS]

The key marker for departmental success is the grades students receive in that subject, as 'Ofsted increasingly uses attainment results as the first step in an inspection' (Perryman et al., 2017, p. 11). School priorities are frequently driven by examination outcomes (Ofsted, 2017), both because schools are ranked annually in league tables by their examination outcomes and because school data are the starting point for school inspections (Ofsted, 2017). None of the schools felt that the collaboration would help to improve students' grades in external GCSE examinations or that it would be considered evidence of good practice by Ofsted. As already discussed (in Chapter 6), at Beebury they were planning to reduce their integrated teaching as they felt that it did not help in the high stakes GCSE examinations. The other collaborations are probably too small to have a significant effect on grades and outcomes – a one or two-week project, a few lessons, will not make a significant difference over five years of education. The aim of collaborating was not to improve grades in most cases although, with the increase in mathematical content in science and other subjects, it may be an aim in future. As FML explains, if it can be shown that collaboration will help with progress towards targets then it will be prioritised:

> *I think it'll be like lots of things in education, it* [collaboration] *will be driven from exams and assessment and then it'll happen* […] *And it's all tied up with the, you know, the data, the tracking, the targets and at the end of the day, if that's what you're assessed on, if that's what children leave school with and they're assessed on, it's going to be the driving force*. [FML]

7.4.3 STEM agenda

STEM was discussed in four (Ayford, Beebury, Ceeton and Eyston) of the schools visited – I did not introduce the term but it was mentioned by teachers during the course of the interviews. In Ayford, where there were definitely discrete science, technology, and mathematics lessons, ATL commented that there was a limited quantity of STEM in the school. As ATL could clearly not be referring to the individual lessons, 'STEM' must be being taken to mean integrated or collaborative activity. In all of the schools it appeared that they interpreted STEM as interdisciplinary working. For example: *'Cross-curricular work, STEM work*' [AS]. Sometimes STEM was only involving maths and science. For example: *'We* *then ran our Year 9 STEM project, that's what we called it, however it was just science and maths'* [AS].

Ayford and Beebury were the schools where STEM was discussed the most and in both there was the concern that STEM should be for everyone not just for an elite or for those who signed up to a 'STEM club'. BSL also highlighted that STEM clubs, in schools in general not just Beebury, frequently did not involve much maths: *'It's far too often STE and there's not enough M in there'* [BSL].

7.4.4 Staffing

There are national issues with both recruitment and, particularly, retention of teachers, especially physical science and mathematics teachers (House of Commons Education Committee, 2017). Issues with staffing – particularly departments being short staffed, coping with staff extended absence, dealing with rapid turnover or with staff who are struggling for any reason – was a factor in reducing or ceasing collaboration, as the following quotes exemplify:

> *We've been a more troubled department and it* [collaborating] *has not been the top of our priority list at all* [...] *maybe it is sensible to get your house in order first.* [FS]
>
> *They* [the technology department] *lost a teacher through long term illness, who's now resigned and another teacher who retired at the end of last term, so* […] *they haven't had the capacity to engage with other departments until now.* [AM]

Collaboration was suggested by many participants as adding to workload, for example:

> *I think it's the time, I think that's the big thing, is that it does get pushed to the side, because other stuff, as a teacher, you can just kind of make your work fill your time, I find, if you want to. You could be here from six o'clock in the morning to eight o'clock at night and still not feel you've done everything, so you have to prioritise and as a school you have to prioritise.* [FM]

Time was also recognised as a reason to keep collaboration to the lower years as it would be quicker to plan. At Ayford they had not tried the visiting expert for A-level lessons: '*At key stage 5 I think it would take a lot more careful planning and time to do say a starter for a lesson'* [AS].

AS also suggested that their visiting expert work was successful precisely because it did not take too much time which kept it manageable*: 'I'm a fan of* […] *the manageable strategies* *for STEM ways of working*' [AS]. Time was mentioned in each school and by most of the teachers interviewed as being a limiting factor in collaboration.

It is understandable if senior leaders in schools where there were, or had been, staff shortages choose not to encourage collaboration. Working with another department can lead to challenges to teacher identity as a 'good teacher' or as a 'subject teacher' and a concomitant reduction in job satisfaction. Ball similarly argued that 'introducing new working practices which replace established and cherished ways of working' could 'threaten individual self-concepts' (Ball, 1987, p. 32). In an era of staff shortages, upsetting teachers by threatening their individual self-concept or identity could be seen as a risky strategy – particularly when the benefits in terms of grades in examinations and Ofsted are uncertain.

7.4.5 Summary

A range of national policies have an impact on mathematics-science collaboration. There is pressure on schools to achieve high grades and for a positive Ofsted report, neither of which is believed to be significantly assisted by collaboration. The mathematics and science curricula are found in practice to be very separate, not supportive of each other, and thus the curriculum itself acts against collaboration. The only national policies which were mentioned as being supportive of collaboration were STEM policies and these were felt to be all too often only for the few who might voluntarily attend a STEM club. STEM was interpreted without exception as being interdisciplinary work involving all or some of the four STEM domains, although this is not the way that STEM is interpreted at national level in England as I have previously shown (Wong *et al.,* 2016). There are national shortages of physical science and mathematics teachers, which are likely to make school leaders wary of the potential upset that collaboration could cause staff. Thus national policy was, in general, broadly believed to hinder collaborative efforts at school level.

7.5 Summary

In this chapter I have shown that there are boundaries around individual departments and that, in most schools, the insulation between science and mathematics is strong, created and maintained by a number of factors including language differences and physical spaces. There was frustration at the 'other' department from both sides. Mathematics teachers were frustrated at how science departments use mathematics and, in particular, how it was not used to support students' mathematical development. Science teachers were frustrated that the mathematics curriculum does not support the use of mathematics within science; when added to a lack of understanding of curriculum differences this frustration can lead to the blaming of mathematics colleagues for students' mathematical difficulties.

There were two key ways in which the boundaries could be weakened. The first is by those in a position of power, usually the senior leadership team, although at Ayford it was AM, a highly regarded teacher outside the management structure of the school. Alternatively, informal communication could be established by those in a friendship. Such conversations were valued sources of professional learning, particularly about the similarities and differences between the two curricula.

Science is dependent on mathematics but mathematics is not dependent on science. This asymmetric dependency means that science is likely to gain more from collaboration than mathematics.

The boundaries make it challenging for students to use mathematics in science; in other words, to transfer their learning. Students need to be supported in using mathematics in science and science teachers can struggle to provide such support.

Working closely with colleagues from another department, and particularly being required to teach another subject or teach in a different way, can challenge teachers' identities as both a 'good teacher' and as a 'subject teacher.' Teachers' views of collaboration are shaped by – and potentially shape – their beliefs about teaching, with some perhaps feeling that they are betraying the subject they love when working closely with another department. Thus collaboration styles where teachers can stay in their 'own world' such as the visiting expert model at Ayford were, in consequence, generally more popular than those which required them to teach outside their specialism, by providing less challenge to teachers' identities.

National policies such as the national curriculum, Ofsted and STEM, together with national subject teacher shortages, were felt to act against collaboration, or at least not to be supportive of it. I turn next to the development and enactment of national policy, and present the analysis of the interviews with 21 key contributors to the science and mathematics education discourse in the last 25 years.

Chapter 8
Muddled compromises: science and mathematics in education policy

In Chapter 7, I examined the schools' data through the theoretical lenses outlined in Chapter 4. As each lens was applied, different aspects of the data came into focus providing a richer picture of the relationship between science and mathematics in schools than was possible from the application of a single lens. I showed that school-based participants found many aspects of policy acted against collaboration, particularly the national curriculum, assessment and the government's educational agenda as pursued by Ofsted.

Education in England can be seen as a loosely coupled system (Weick, 1976), with each school individually responsive to national education policy, thereby preserving its own identity through unique adaptation to the local environment. As policy provides the context in which schools operate (Maguire, Ball, & Braun, 2012), a greater understanding of the policy landscape helps to explain and interpret practice in schools. There is not, however, a direct chain of consequence from policy to practice, due to the possibility of local policy interpretation. The term 'policy' is commonly used but difficult to define (Hill, 2013), with Ball suggesting that policy is 'a process, something on-going, interactional and unstable' which is 'often messy, contradictory, confused and unclear' (2013, p. 8).

To try to understand the relationships between science and mathematics in education policy, and to reveal the meanings and motivations of those directly involved with the making and enacting of aspects of that policy, I interviewed 21 key contributors to the science and mathematics education discourse in England. I asked the participants about aspects of government policy and practice, particularly the writing of the national curriculum, the government's STEM initiatives, and mathematics within the science curriculum. The data were analysed as described in Chapter 5, before using three of the lenses described in Chapter 4 ('boundaries and power', 'policy', and 'transfer') to produce a more theorised view.

Most of the individuals interviewed were, or had been, members of organisations or groups which were seeking to influence policy, often through networks. As discussed in Chapter 4, recent governments have increasingly turned to networks of interested actors in the making and enactment of policy, and consequently the 'education policy community is increasingly heterogeneous' (Ball & Junemann, 2012, p. 9). Ball and Junemann argue that such networks 'blur the boundaries between state and society' and 'expose the policy-making process to particularistic power games' (*ibid.*, p. 7). Thus, organisations may compete with each other, at least to some extent, for access to the decision-making sites of government. In consequence, education policy networks can be loosely connected with 'often conflict-ridden members' (*ibid.*, p. 9). There are, therefore, divergent views among the participants and it is challenging to identify the underlying reasons and bases for the positions held, some of which are quite subtle and nuanced.

In other words, there is wrangling, dispute and compromise among and between those interest groups seeking to influence government policy, including curriculum policy, and it is not always possible to see how or why decisions have been made. Such wrangling, however, is nothing new; even in the 1960s, Williams argued that:

> An educational curriculum, as we have seen again and again in past periods, expresses a compromise between an inherited selection of interests and the emphasis of new interests. (Williams, 1962, p. 150)

He went on to argue that the 'compromise will often be muddled' (*ibid*., p. 151). Ball agreed, demonstrating that the 'outcome of these compromises *are* different at different historical moments' (Ball, 1990, p. 214). Fensham (2009) demonstrates the particularly contested nature of science education and argues that in any discussion of policy one should ask whose values are favoured, which stakeholders have been successful in its shaping and which groups in society are advantaged and disadvantaged by resulting education practices.

In this chapter I will begin with the study of two cases of policy development which are directly applicable to science and mathematics education: the national curriculum and the government's STEM initiatives. I will then consider the relationship between school science and mathematics education through the lenses of power and boundaries, policy, and transfer. In so doing I will demonstrate the contested nature of science within government education policy and the perceived reasons for collaborating – or not collaborating – across science and mathematics at policy level. Throughout, I will show the muddled, messy and unstable nature of policy and policy making.

8.1 Relationships between science and mathematics in policy making

8.1.1 Writing the national curriculum

In this section I will explore the writing of the national curriculum through the recollections of those involved. I will focus particularly on the first national curriculum from 1989 and the most recent, which was being written as the interviews for this study were being carried out, with a brief look at the era of QCA.

8.1.1.1 The first national curriculum

The national curriculum was conceived originally as a set of 10 subjects which children would study in school. They were, to use Bernstein's (2000) terminology, strongly classified as discrete entities and thus from the start there was limited coordination or collaboration between them. The relationships between and across any of the subjects, including those between mathematics and science, were ignored in the initial creation of the national curriculum as SE recalls:

> *When the science group was set up, I asked the Secretary of State whether or not we were a science group in the context of a framework for the whole curriculum* […] *It was quite clear that the Secretary of State didn't have a notion of a whole curriculum but that he knew he wanted maths, science and English.* [SE]

As Orton and Roper had identified, 'the possibilities of co-ordination were ignored in the creation of the national curriculum' (2000, p. 135). The government decided which subjects were to be included and the programmes of study were written by completely separate working groups. Membership of the working groups was based on recommendations from HMI and DfE officials, but some suggestions were vetoed by the Secretary of State and even the Prime Minister, Margaret Thatcher (Ball, 1990). As the writing of the curriculum got underway, there was very limited collaboration across the mathematics and science working groups.

> *There was no formal linkage at all between* [the working groups]. *The support from the department was such that we operated in channels.* [SE]

The mathematics group got into considerable difficulties, particularly regarding opposing definitions of what counted as school mathematics, and had to start again with a new chair who was very keen that the report be delivered on time (Ball, 1990), as discussed in

Chapter 2. In consequence, members of the mathematics working group were barred from talking to people on the science group by the mathematics group chair for fear of distraction, although the order was not always obeyed:

> *I knew a number of the people on the science group quite well. I used to have conversations with them, but we were ordered by the chair of the maths group not to talk to the science group, so all my conversations were completely clandestine. But it was nonsense, you know, to be developing a total new national curriculum for maths and science not to talk to each other* […] *He felt we were behind* […] *He thought talking to the science people might distract us from the task. I can understand where he was coming from but it didn't excuse it.* [MA]

The lack of collaboration between groups was also government policy, as SC recalls:

> *My group recommended that the different groups should put their heads together over what they were doing and the ministry did set up a meeting between the scientists and the mathematicians* […] *But it was clear that their heart wasn't in it and no subsequent meeting happened* […] *I knew people on both the maths and the science working parties pretty well and we did talk to one another anyway.* [SC]

It is not clear what impact the clandestine conversations had on the resulting programmes of study, but they did not lead to formal linkages between the curricula. The science group clearly had to include mathematical ideas within science, but their inclusion was not informed by discussion with the mathematics working group. There were apparently no conversations about what students might be expected to do and when; the science group used their considerable experience to determine which mathematics would be appropriate at any given point in the science curriculum, as SE explains:

> *We bore in mind whether or not the* […] *mathematical burden was going to be too high to introduce the mole concept now or a statistical approach here for biology. But it was that kind of thing* […] *rather than any matching of cognitive ability or development in maths with the concepts in science.* […] *Of course we brought all kinds of experience from other places* […] *but it was sort of thrown into the pot as we were developing it rather than saying 'now we'll check this out with what the working group in maths are doing'. There wasn't a lot of that. I mean part of it was that there wasn't a lot of time.* [SE]

It was believed – or hoped – by some of the interviewees that civil servants would provide the match up that they were aware was not present across the curricula. For example:

> *Afterwards there was a bit of retro-fitting by the civil servants, I think.* [SH]

Thus there was an acknowledgement of a requirement for collaboration, or at least harmonisation, across the two curricula even if there was no direct recollection of it actually occurring – demonstrating the confused and messy nature of policy making. The difficulty with relying on civil servants to do this work is that they are not subject specialists and do not have teaching experience. '*The civil servants frankly don't know a lot about subject knowledge*' [MA]. It is not their role to do so, which is why the subject working groups were established.

Ball demonstrates that in this phase of curriculum policy making, 'the locus of decision making is located firmly inside the educational state, to the extent that significant aspects of school mathematics are being discussed in Cabinet sub-committee' (1990, p. 204). While there were members of the educational establishment and representatives from industry present in the working groups, there was an 'unprecedented level' (*ibid*.) of government control over the details of the curriculum – and the government preference was for individual subjects not for an over-arching or whole curriculum.

8.1.1.2 Revisions to the curriculum – QCA

The curriculum has been reviewed and adapted multiple times since it was first written (see Appendix 1). Revisions for key stages and subjects have been written and introduced at different times, making it more difficult for them to be linked together. However, there was some attempt at linking them by QCA:

> *I think a curriculum where* […] *the two groups actually sit down and work things out together* […] *QCA used to do that, when they developed the 2007 curriculum and the one before that.* [SK]

The 2004 version of the national curriculum for key stages 3 and 4 (DES and QCA, 2004) was unique in including links between the subjects. The science curriculum noted links to mathematics and to English in the margins; mathematics only included links to English. That such links sent out strong messages about the order and hierarchy of the subjects was noted by SJ:

> *I do remember at the time saying, so what's going to be in the margins for maths and there isn't any, except for English. So the overall architecture was very much a*

> *hierarchy of subjects, you know, first you need to speak, then you need to do numbers and then you use those in other subjects. So other subjects are an opportunity for you to apply your English and maths skills. So what it means, I think, is there was less encouragement for the maths specialist to consult others. They were seen as the foundation for other subjects, other subjects had to learn from them, rather than vice versa, was the overarching sense.* [SJ]

MB worked at QCA during the development of a later revision and suggested that the organisation did manage to integrate the subjects to an extent:

> *I wanted those* [STEM] *subjects joined up, I wanted some integration across them and I thought if we could get some integration into the curriculum we were developing* […]. *We did quite well with the* [2007] *science and maths, less well with ICT and we failed with D&T.* [MB]

However, QCA became QCDA before being abolished in 2010 without any significant objections from the education community.

> *Getting rid of the independent curriculum body was a major move and it went without anybody arguing much about it, which I thought was very strange.* [SC]

The lack of objection was in part because QCA was not very popular with the educational establishment, but MA suggests that it was better than the alternative:

> *I said at one point I never thought I would mourn the absence of QCA, but I'm beginning to see that actually it did play a part in a number of things. And I think one of them is having this kind of professional group that has a responsibility for the curriculum and so I think we're now really quite dependent on the DfE*. [MA]

Although QCA reported to the government, it was a semi-independent and professional body with responsibility for the curriculum. With its demise, curriculum policy making is now located inside the Department of Education, meaning the locus of decision making is once again firmly inside the state machinery.

8.1.1.3 The most recent revisions to the mathematics and science curricula

The programme of study for each subject in the original national curriculum was written by one working party who wrote the whole curriculum from 5-16. At QCA the entire curriculum was written within the same organisation. The most recent key stage 4 National Curriculum was written by a small group for mathematics and for science by one biologist, two chemists and one physicist, each separately contracted to write the content for their subject.

SC, one of the science group, suggested that for the most part the science group were not steered significantly by the Department for Education:

> *Science is a bit more of a mysterious art to those who aren't scientists so they have actually left* […] *us more or less alone in that they haven't imposed on us any particular view of science.* [SC]

The curricula were commented on during development by the various learned societies acting through SCORE (SCORE, 2014), but huge power was given to a very small group of writers to present their view of science in the GCSE. Although SC suggests the view of science may not have been directly steered by the DfE, there was a government decision to include more and specific mathematics within the GCSE science content. In other words, the view that science should be more mathematical was promoted and prevailed:

> *The ministers were particularly keen for the science, that we put in for each main topic the mathematics requirements.* […] *For each topic there's a separate maths requirement. We were asked explicitly to do that. We were not asked by the mathematicians, we were asked by the people at DfE.* […] *And putting in the mathematics seemed to me to be a perfectly sensible thing to do because* […] *the use of maths, particularly in physics* […] *had been neglected in the GCSEs up to that point.* [SC]

Thus considerably more mathematics was included within the GCSE science content at the request of the DfE, not the mathematicians. There was, however, no consultation with the mathematics writers:

> *There hasn't at the moment but in the draft documents there is much more specificity about where the maths is to be done* […] *Now I can envisage that* […] *there needs to be a conversation with the maths community to ensure that the maths is done at the same time* [… or] *ahead of time.* [SA]

In other words, SA is expressing a belief that when they came to have a conversation with the mathematics community it would be to ensure that the mathematics curriculum meets the needs of the science curriculum. The writers of the science curriculum used their existing knowledge of mathematics, much as the writers of the original national curriculum had done, as SC explains:

> *I think I know enough about the maths curriculum at that level* […] *we were trying to fix it at an appropriate level that anyone doing GCSE maths would be able to handle and apply.* […] *We were trying to tune it to current, or previous really, expectations in mathematics at age 16.* [SC]

As the mathematics writing group was not consulted, it was not possible to 'tune' the mathematics content to the current curriculum, it could only be aligned with the previous, now out of date, version. ME, who contributed to writing the current key stage 4 mathematics curriculum agreed that they had not been consulted but suggested that civil servants may have shared necessary information with the science group:

> *Just because we weren't consulted didn't mean to say that they didn't see what we were writing so I think the civil servants did share a lot of it between them.* [ME]

Even to some in the policy sphere it was unclear who had responsibility for writing the latest round of curricula, particularly key stage 3 science:

> *The current curriculum has been written by, oh, God knows who it's been written by really, and it certainly hasn't helped collaboration.* [SK]

There have thus been several iterations of the national curriculum. The 'locus of decision making' (Ball, 1990, p. 204) has moved from being firmly located in the State, out to a professional body responsible for the curriculum, and back to the Department for Education. It would therefore appear that there was some coordination between mathematics and science in the era of QCA, but very limited coordination when the writers were separately contracted directly to the DfE. I have demonstrated, however, that ensuring consistency and linkages between and across the science and mathematics curricula has generally not been a high priority in curriculum development.

Bernstein argues that:

> As a consequence of the national curriculum (and its many revisions) there is a stronger classification, for this curriculum is a collection of singulars (subjects) where commonalities are not effective in practice. (2000, p. 61)

Thus it is perhaps not surprising that where subjects are so strongly classified there is limited coordination or collaboration between them.

8.1.2 The national STEM policies

The national STEM policies (2002-2011) brought science and mathematics educators together, at least in the government's High Level STEM Strategy group (as discussed in Chapter 2). However, far from harmonising policy, the emergence of STEM has made a messy policy landscape even more contested, as it is unclear where STEM came from, what it means or how money should be distributed within it.

Bernstein describes individual subjects as singulars and recognised that singulars can be brought together into larger groups that he calls regions: 'Regions are constructed by recontextualising singulars into larger units' (Bernstein, 2000, p. 52). Regionalisation can perhaps be seen in the bringing together of biology, chemistry and physics to construct the region of school science. More recently, regionalisation can be seen in the clustering together of science, technology, engineering and mathematics to form STEM. Bernstein argues that:

> Any regionalisation of knowledge implies a recontextualising principle: which singulars are to be selected, what knowledge within the singular is to be introduced and related? [...] Every time a discourse moves, there is space for ideology to play. (*ibid.*, p. 9)

The participants were unclear as to what ideology had led to those disciplines being clustered together. For example one respondent said:

> *I'm thinking it came more from the DTI[3]/business side of things because that collection of subjects made sense in the wide world of business when they didn't necessarily in schools.* [SD]

Even John Holman, the UK National STEM Director has admitted not understanding the logic behind the bringing together of these four subjects: 'Whatever may have led us to cluster these subjects together, it cannot be their similarities, because they have few' (Holman, 2011, p. 6).

Among participants there was considerable agreement in their dislike of the term STEM. For example two commented:

> *It is an acronym which is, I think, completely fatuous*. [MD]

[3] Department of Trade and Industry

> *It's not a term that the ordinary person in the street understands, and it can be confusing with stem cells, and it has this mixture of technology and engineering, probably so that it makes a word rather than any other reason.* [SI]

A number of interviewees mentioned STEM as having come from SET – but aside from the Roberts' (2002) Review, no one knew where that collection of subjects had come from either. SET was the original discourse in England which arose following Roberts' (2002) review. Mathematics was deemed to be part of this discourse from the outset, although it was not part of the acronym. The initial SET agenda was perceived to be strongly dominated by science, to the extent of being a science agenda, as recalled by MC: '*There was a science S-E-T agenda'*.

Mathematics educators were part of the network governing SET initiatives, but felt that mathematics was excluded and invisible, in part as it was not in the acronym SET, as MA recalls:

> *I remember at every meeting saying 'maths is supposed to be included in this' and 'where's the maths, I can't see it'.* [MA]

Both mathematics and science educators recalled strong and heated discussions regarding the place of mathematics, for example:

> *One of the things I, along with other mathematicians, said maths should be there. And I remember an interaction with Lord Sainsbury and he said 'well, it is there, everyone knows it's there but it's sort of invisible'. And I said, 'no it's not. If it's invisible you don't see it'*. [MC]

The feeling of being invisible, of needing to fight to be a seen and acknowledged part of the agenda was mentioned by a number of mathematics educators but none of the science educators, although one did talk about whether STEM was an attempt to change the status of engineering and technology to that of science, which clearly caused some unease:

> *There was discussion between the communities about whether* [STEM] *was about positioning engineering and technology to have the same status* [as science] *and what that would mean.* [SD]

In joining up with STEM, some mathematics educators felt that mathematics became less consequential, as MC explains:

> *SET obviously involves maths and that was quite good but we kept maths separate, but then it all came under STEM and then maths became a bit less important. It's become important again now.* [… STEM] *is important, it's just there are other things in maths than science*. [MC]

Like MC, many of the mathematics educators talked about mathematics having links to far more disciplines than the STEM subjects, including social sciences, economics, computing, art and the need for basic mathematics and numeracy for the whole population. Several mentioned the risk that joining up with STEM would suggest strong links to science, meaning mathematics could be perceived as prioritising the needs of the science community and thus apparently privileging some reasons for studying mathematics ahead of others. As there is no part of science that does not fit within STEM, there are not the same conflicts for science educators; none of the science educators saw themselves as invisible or side-lined. There is evidence, though, from the quotes from SD and MC that both science and mathematics educators felt threatened by the appearance of STEM. SD recalls discussing whether technology and engineering would have the same status as science; MC that STEM made mathematics less important.

Bernstein argued that:

> Regionalisation as a discursive procedure threatens pedagogic cultures dominated by singulars […] Increasing regionalisation necessarily is a weakening of the strength of the classification of discourses. (2000, p. 52)

I previously suggested that policy makers disliked the term STEM as they were not sure of its provenance (Wong *et al.,* 2016); perhaps the dislike also came from feeling threatened about what the new regionalisation would mean for the individual subjects.

Bernstein also proposed that: 'New power relations develop between regions and singulars as they compete for resources and influence' (2000, p. 9). Prior to the rise of STEM, there had been money for science education and for mathematics education, with the budgets tending to be separate. Now they were together with one committee to oversee the spending – a situation that led to fights and competition over how the budget would be spent, as one participant acknowledged:

> *Funding went to STEM and within the STEM envelope folks fought over whether it would be maths funding or science funding.* [EA]

There was also an acknowledgement from participants that there was no single clear definition of STEM. When we use the term STEM are we sharing an understanding of what it means? One interviewee used a chemical analogy to ask if STEM is a mixture of different disciplines put together as separate entities, or a compound with the disciplines reacted together to form something new. These two conceptions are profoundly different.

Some respondents suggested that different sectors had interpreted STEM in different ways as the following quote exemplifies:

> *At national level it* [STEM] *means the supply of people, home-grown people with the appropriate skills to service the STEM sector of the economy. At school level it means interdisciplinary work between the subjects of science, technology and mathematics. So it means two completely different things*. [MB]

I demonstrated in Chapter 7 (Section 7.4.3) that, in the schools I visited, STEM was, as MB suggests, interpreted as interdisciplinary work.

In summary, there was confusion as to the 'recontextualising principle' (Bernstein, 2000) which was used in the bringing together of the four disciplines of STEM. None of the participants knew where STEM had come from or why those disciplines were brought together, but it was not believed to have arisen from an educational imperative. Bernstein predicted tension between regions and the singulars which have been brought together to constitute the region, and such tension is seen in the data in responses querying the status and importance of the various subjects within STEM and even what the region, STEM, is or should be. Bernstein similarly predicted competition between regions and singulars for resources, a phenomenon which I have likewise demonstrated in the data. Thus, while STEM brought science and mathematics educators together, at least as part of the High Level STEM strategy group, the net result was tension and conflict at least as much as collaboration.

8.2 Power and boundaries

8.2.1 Relationships across the boundaries

In Chapter 7, I showed that, as Bernstein (2000) argued, there are boundaries around subject departments in schools. There are boundaries, similarly, among those seeking to influence policy in England. That collaboration across those boundaries was challenging is easy to see in the data and there was even disagreement about where the boundary should be drawn. For example, some participants questioned whether we should consider school science as a whole or as the separate subjects of biology, chemistry and physics, chiming with Jenkins (2007) who argued that school science is a 'questionable construct' as the individual sciences are so different. Similarly, some participants suggested that science includes mathematics (for instance, 'actually mathematics is part of science,' MD), although the majority of mathematics educators interviewed did not agree. MA even considered being seen as part of science as dangerous:

> *There's a real danger that maths is seen as a kind of small subset of science; that's how the science people see it always.* [MA]

In spite of disagreement about where the boundaries lie, all participants identified that there are boundaries between subjects and they used the language of divisions, barriers and silos to describe them. For example:

> *We are very good in this country at creating little silos. We're clubby* […] *We're like that. It's almost as if we can't handle society as a whole, we need different groupings. So subjects, cognate disciplines are protected with 'we're different from you'.* [MD]

There was no consensus as to whether these silos should be broken down through collaboration or simply accepted as the way the culture of education has developed over the years. For example, SD could see no reason to change the way things are:

> *Well, there are obvious barriers within schools in terms of the way we* […] *have constructed the idea of subjects. That we have specialists who teach those subjects and those specialists are trained in certain ways and even sit in certain departments in schools. You know, we have got that, and there's nothing obviously broken about it – so why, why, would we try and change something that has built up over years, that has cultures and geographies and even resources that perpetuate the barriers, if nobody can think of any real reason why?* [SD]

Maintaining the lines of communication across boundaries takes work. SD suggested that, for the science community, the focus of any relationship maintenance is within and across the various branches of science itself:

> *I think for science there's enough of a struggle* […] *for the different science communities to work together and to understand each other* […] *it's so different and diverse as it is, that there's so much effort to keep the communication and co-operation going within it is all that people can sustain.* [SD]

SD also felt that the willingness to work with mathematics educators was there within the science community, but that working with the other members of the science community would always be prioritised over working with mathematics.

> *There's a sense of, well if we get that* [cooperation within science] *sorted then of course we'll start thinking about wider and bigger, but you never do get that sorted.* [SD]

In sum, the majority of the participants agreed that there are boundaries around the various subjects, even if they did not agree where those boundaries were. The majority of the participants prioritised collaboration within science or within mathematics itself over collaboration with the 'other', believing that collaboration just within science or within mathematics was demanding enough.

8.2.2 Boundaries and asymmetry of dependency

In Chapter 7, I showed that science is dependent on mathematics, agreeing with authors including Osborne (2011, 2014) who identified two of the eight practices of science as mathematical. The dependency of science on mathematics was a recurring theme among the policy participants too, as the following quote exemplifies:

> *Mathematics is absolutely fundamental to lots of science so I think it is right that we shouldn't shy away in science teaching from maths, where the maths is important to the science.* [CSA]

There was also an acknowledgement that the further students go in their science studies, the more there is a need for mathematics. For example:

> *Science in schools* [is] *highly dependent on maths. When it came to kind of getting people out into undergraduate degrees and into A-level you actually needed a bit of solid maths there.* [MA]

> *The unfortunate challenge of all science* [is] *that you can get so far with concepts and ideas and illustrations but to get beyond a certain point needs mathematics.* [MD]

Concurring with the teachers interviewed (Chapter 7), none of these participants suggested that mathematics is dependent on science.

Several of the interviewees, including many of the mathematics educators, noted that engaging students with mathematics can be problematic as they often find it difficult and dull, as the following quotes exemplify:

> *Maths can be a bit boring sometimes.* [MC]
> *Maths has its own pressures because everybody knows it's important, but actually how do we get more people to enjoy it?* [SJ]
>
> *I mean what* [the Smith] *report*[4] *basically said was 'Look, maths is a* […] *difficult subject for 16 year olds'.* [MD]

None of the interviewees mentioned science being dull or difficult, although there is plenty of research to suggest that students often find it so (see, for example, Osborne & Dillon, 2008). Some participants suggested that the 'dullness' of mathematics could be improved by using interesting contexts, and that science could potentially be a source of such contexts. For example:

> *You have the typical statistics in maths questions of 'Ali goes out to a car park and counts how many red, yellow, green and black cars there are'. Where actually there is wonderful data available from lots of subjects which would be real, much more exciting for the maths* […] *science can provide much better examples to carry the maths.* [MF]
>
> *One of the ways of making the teaching of maths more engaging is to show how it has applications in, and is indeed in the foundation of, a lot of science.* [CSA]

SD suggested that resources aimed at giving mathematics a science context often used the science just as a 'story' to wrap around the mathematics:

> *From my perspective, it looked like maths teachers doing* [resources] *with a kind of biology story wrapped around them. They wouldn't help a biology teacher use them and a maths teacher wouldn't teach the context; they wouldn't necessarily be interested in it.* [SD]

In the example cited by SD (above), the fact that the resources were in a biology context would neither help to further students' understanding of science nor help biology teachers to use mathematics in science. In fairness, that is not what they were intended to do, they

[4] Smith (2004) *Making mathematics count*. London: HM Stationary Office

were written by mathematics educators to improve students' understanding of mathematics. The point is, that even in these science-context resources mathematics is not dependent on science. MC agreed that STEM provided many good contexts for mathematics, but raised a note of caution that when teaching within a context, care must be taken not to lose sight of the original mathematics: *'*[STEM] *really does give that context and excitement* […] *But don't lose the maths'* [MC].

The mathematics getting 'lost', in other words being side lined or under-emphasised, when it is taught within a STEM context may help to explain the finding of Becker and Park (2011) that when mathematics is taught in an integrated context with one of the other STEM disciplines, mathematics attainment can be lower than when it is taught separately. Perhaps so much focus can be put on the exciting context that the mathematics, and thus the mathematics learning, gets lost. Teaching mathematics within a science context is an example of changing the insulation and classification between the subjects. Bernstein (2000) argues that when the classification changes, when the insulation between the subjects weakens, we must ask who benefits.

As a result of the asymmetry of dependency, identified in Chapter 7, there is usually greater potential for science than mathematics to benefit from any collaborative activity. Although these findings hint that there can be benefits for mathematics if it is made the focus, or is at least brought to the fore, collaborating with science is not risk-free for mathematics and thus the reluctance of many in the mathematics community to have a closer relationship with science is understandable.

8.2.3 Power, service and ownership

While there is broad agreement that science is at least partly dependent on mathematics, it is less clear where such a dependency leaves the relationship between the two disciplines; whether the dependency of science makes mathematics a 'servant' of science. As discussed in Chapters 4 and 7, there is a tension within mathematics education between the pressures of being a service subject and the requirements of mathematics as a discipline in its own right (Hoyles, Newman, & Noss, 2001; Smith, 2004). Bell (1951) titled his book 'Mathematics: Queen and servant of science' in acknowledgement of the dual, and apparently oxymoronic, role mathematics plays in the relationship between the disciplines. For many of the mathematics educators, the idea of being a 'service subject' was contentious. MA acknowledged that part of the reason why mathematics is one of the core subjects was its utility to other disciplines:

> *Of course it's fun to do pure maths, I mean that's nice, but actually we wouldn't have 5 lessons a week or 3 hours a week, or whatever it is, if it wasn't a big component of other subjects and important for that reason.* [MA]

However, for MB this idea of being a 'service' subject is deeply problematic, probably because it carries the idea of being subservient:

> *Mathematics has never wanted to be viewed as a service subject for science and technology – and indeed it isn't – and as the finance sector shows, even if you view it purely as a service subject, it is a service subject for a lot more than just science and technology. But of course, it's not just a service subject, it's a subject in its own right as well.* [MB]

The dependency of science, and other subjects, on mathematics raises the question as to who has, or should have, ownership of the mathematics curriculum. In other words, who should control the content and sequence of the mathematics curriculum: mathematicians or users of mathematics? Bernstein (2000) argues that there is selection in how one discipline 'is to be related to other subjects, and in its sequencing and pacing' (Bernstein, 2000, p. 34). Such selection always involves ideology (*ibid.*); there can therefore be differences in ideology and in what people believe to be the ideal sequencing and pacing of the curriculum. For example, the dependency of science on mathematics can lead to science educators believing that they should have some say in the content and sequencing of the mathematics curriculum. Indeed, in Chapter 7, I showed that the mismatch in timing across the mathematics and science curriculum was deemed problematic by many of the teachers. SA similarly discussed the timing mismatch:

> *When they do certain bits of mathematics in the mathematics curriculum that would be relevant in the science curriculum, then they are not even approximately, remotely at the same time.* [SA]

The secondary curriculum is arranged in key stages, with content set out for two to three years at a time. It is quite hard, therefore, to see how two subjects could align to the degree of being taught 'at the same time' except by negotiation at school level which, as we have seen, is unlikely to happen.

SI argued that linking the mathematics and science curricula would bring benefits to science education:

> *I mean, the mathematicians do see themselves as a little bit different, because they always argue that* […] *'We don't just supply maths for scientists and engineers'. Which is fair, but I still think we could benefit, because of the use of the maths, we could benefit more from linkage.* [SI]

SI similarly argued that mathematics A-level should accommodate the needs of the physics A-level:

> [They should be] *correlated in the sense of using the same symbols and guaranteeing that certain maths will be done by a certain time and vice versa, so that, for example, calculus can be done in year one of maths and the physicists could then use calculus in year two of the A-level.* [SI]

Thus the ideology or belief of some science educators is that the content and sequence of mathematics qualifications (at GCSE and A-level) should be arranged to support and benefit science qualifications. Indeed, some mathematics educators at least partly agreed. MH felt that when the mathematics curriculum was being reviewed, the government should have included some users of mathematics on the panel, rather than simply mathematicians:

> *I still feel that the government needs to look wider and look at people who may have had more diverse experiences and especially recognise that mathematics is a service subject, alongside being a subject in its own right. I think not bringing on good users of the subject is a weakness.* [MH]

Not all the science educators believed that mathematics should accommodate science. SB suggested that expecting mathematicians to be the 'providers for scientists' was probably not tenable:

> *I think it is difficult for mathematicians to accept enthusiastically the role of being providers for scientists as against people who enjoy and want to convey the beauty and enjoyment of their own subject. I think that's a tough call for them and, you know, people don't go into mathematics teaching, I guess, because they want to help their science colleagues; they go into mathematics teaching because they like maths.* [SB]

It is perhaps understandable if physics and mathematics educators should take a different view of the relationship between the subjects: while 80 percent of physics A-level students take mathematics, only 32 percent of mathematics students take physics, dropping to only 15 percent of female students taking A-level mathematics (Gill, 2012).

The ideology, or even expectation, of ownership of the mathematics curriculum on the part of some science educators is perhaps why MA suggests that being seen as ‘a small subset of science’ is dangerous. If mathematics is a part of science, especially if only a small part, then the science education community could potentially claim the unwelcome right to exert influence over the mathematics curriculum.

8.2.4 Language boundary

The language boundary is revealed in the different terminology used in mathematics compared to science, as discussed in Chapter 7, but also in the way that people talk. Siskin reported that even when not talking about their subject, teachers’ ‘disciplinary background reveals itself in the choice of words, the structure of their arguments, or the goals they hold’ (1994, p. 153). Siskin was talking about teachers, but the same could be said of the participants in this study for whom a particular disciplinary background was clearly apparent in the figures of speech people used. Mathematics educators made comments such as: ‘*Their Venn diagrams look different*’ [MG], and ‘*decisions happen in a very binary fashion*’ [MH]. Similarly, a science educator with a chemistry background asked if STEM is a *‘mixture or a compound?’* [SE].

Metaphorical language such as the examples above are quirky and hint at the speaker’s background, but would probably not limit understanding across mathematics and science educators. There are, however, more fundamental variations which could limit communication. For example, there is a difference in the way in which numbers and units are used, as SF explains:

> *Lots of science teachers use what you might call quantity calculus so a physical quantity is a number and a unit. Maths teachers don’t. They have a formula and they substitute a number in it and magic up the units later.* [SF]

Science tends to use quantity calculus or values rather than pure numbers. Values have a unit as well as a number and these impact whether and how those numbers relate. In the simplest terms it is not possible to add two numbers if they have different units; one cannot add length to mass. SF further contends that the way that science teachers talk about mathematics is different from the discourse of mathematics teachers, resulting in a disconnect in the way in which the language of mathematics is used across the two domains. In discussing the development of the most recent national curriculum, SF asks:

> *Have they* [the authors] *talked to the maths people? I don't know – but it doesn't look like it from the language they're using. They're using the traditional maths-in-science language and I don't detect much influence of mathematics or teaching in maths.* [SF]

SD similarly suggested that mathematics teachers and biology teachers talk in different languages, largely as the mathematics within biology is within the context of biology, and that this is a significant boundary to be crossed when collaborating with mathematics colleagues:

> *I think there are a number of biology teachers who are aware that they have to get to grips with what their maths colleagues are doing. I think a number of them don't feel massively comfortable about that. I think they feel that they talk in different languages and I think in biology it's so much contextualised that I'm not sure there's a feeling they feel they would benefit from talking to maths colleagues who do not contextualise.* [SD]

Redish and Kuo (2015) argue that the differences in the way mathematics is used across physics and mathematics are significant enough to amount to a difference in dialect or even a different-but-related language. They argue that physicists make meaning with mathematics in a different way to mathematicians, partly due to a difference in purpose; physics (and indeed science more broadly) is concerned with representing meaning about physical systems, where mathematics is more often concerned with abstract relationships. The 'quantity calculus' discussed by SF arises from this focus on physical systems. As a result:

> Physicists ''load'' physical meaning onto both symbols and numbers in a way that mathematicians usually do not […] It allows physicists to work with complex mathematical quantities without introducing the fancy math. (Redish & Kuo, 2015, p. 565)

In other words, the symbols (and their related units) are 'used to convey information omitted from the mathematical structure of the equation' (*ibid*., p. 567) and 'ancillary physical knowledge—often implicit, tacit, or unstated' (*ibid*., p. 568) is used when applying mathematics to physical systems. Using physical knowledge when applying mathematics to physical systems might involve knowing the limits to the numbers which can be put into an equation. For example, in the ideal gas equation (PV=nRT) none of the values would be negative as pressure, volume, amount of substance, the ideal gas constant and temperature in Kelvin are always positive values. There is no mathematical reason why a negative number could not be introduced into the equation, but there are reasons based on physical knowledge. Redish and Kuo (2015) argue that using this physical knowledge helps to keep the mathematics more straightforward. There may, therefore, be good reasons for what SF describes as 'maths-in-science' language and for differences in how mathematics is used in science compared to how it is used in mathematics.

MF gave the example of Hooke's Law, where the same idea is used in mathematics and physics but the notation is different. It can be expressed as:

(i) $T = \frac{EA}{l_0}x$ (ii) $T = \frac{\lambda}{l_0}x$ (iii) $T = kx$

Where x is the extension, T the tension in an elastic string, A the cross-section, l_0 the natural length, λ the modulus of elasticity and k the stiffness. In version (i) E is called Young's modulus and is a property of the material out of which the string is made. Version (i) is usually used by physicists and engineers. Mathematicians tend to use versions (ii) or (iii); (ii) where the length of the string is important, (iii) where neither the length nor area is relevant. While the equations look different, they are equivalent as: $k = \lambda/ l_0 = EA/l_0$. It may not be immediately obvious to students that the equations are equivalent, especially when they are referred to by different names.

MF explains:

> *There are reasons why it is done like that – physicists are more interested in the properties of materials whereas mathematicians are interested not in the materials themselves but in the consequences of that, and that's represented in those different ways.* [MF]

MF argues here that the differences in usage and notation are there for a reason and should not be eliminated, further suggesting that such variety goes beyond that between mathematics and science:

> [Most subjects] *have their own notations, their own ways of describing things. And actually it's very unhelpful that maths departments don't on the whole know this.*

> […] *Where there are differences in usage and notation we should be explaining them.* [MF]

MF therefore argues that mathematics teachers should know the notation of other subjects as well as their own and be able to explain why they are different. This is clearly a tall order for mathematics teachers as there are so many other subjects which use mathematics.

SI, however, felt that mathematicians should change the way that they use notation to be the same as in science:

> *Using the same notation, for goodness sake, in maths as in physics. 85% of the people who do A-Level physics do A-Level maths* [so] *it would be very sensible for the physics and maths A-Levels to be correlated* […] *in the sense of using the same symbols.* [SI]

For all these respondents, and several others, the critical issue is clarity for students who are studying both mathematics and science. Some, like SI, suggest that clarity is best achieved by using the same symbols across both domains; with mathematics using the notation of physics. Others, like MF, suggest that there are reasons for the differences, which should be communicated to students. Redish and Kuo argue that part of the 'acculturation of a physics student is learning to interpret the math physically, not to only focus on mathematical structure and manipulations' (2015, p. 567). This need for physical interpretations of mathematics results in different versions of Hooke's Law being used by mathematicians and physicists. It is perhaps more reasonable, therefore, to keep the differences and to draw students' attention to them, rather than expecting curriculum change in mathematics in order to better suit the needs of science.

8.2.5 Elitism and intellectual boundaries

Western democracies (although not all other cultures) prize logical-mathematical thinking (Crombie, 1994) more highly than other types of intelligence (Caprara & Cervone, 2000), potentially leading to an intellectual ranking of subjects according to the extent to which they depend on logical-mathematical thinking. For example, MD posited that:

> *Maths is a little bit different. Mathematicians are different* [...] *They do confront a genuinely intellectually challenging, elite subject. It really is the Olympics, mathematics is. And not many mortals are up to it, frankly. And I think if you go*

> *through the rites of passage to become a mathematician you do become, or many of them become, just a touch insular, which is understandable.* [MD]

If some subjects rank highly because they rely heavily on logical-mathematical thinking, then, consequently, others rank less highly. Of the sciences, biology is the least reliant on mathematics: in the GCSE subject criteria 10 percent of the marks must go on mathematical skills, compared to 20 percent for chemistry and 30 percent for physics (Ofqual, 2015). In the latest curriculum there is an increase in the amount and demand of mathematics across the sciences, including within biology, which SD suggests could prove difficult for some biology teachers:

> *There will be many biology teachers who managed to avoid doing maths during their degree, managed to avoid a lot of the quantitative things.* […] *They're going to have to get support and they're going to have to get training but I'm not entirely sure what is the right thing to get from their maths colleague down the corridor.* [SD]

It could be difficult for a science teacher to admit to a limited knowledge of mathematics, and consequently have to face an elitist boundary structure, particularly as logical-mathematical thinking is so highly prized and scientists are often expected to be highly numerate (as discussed in Section 7.3.4). Yet in spite of the higher intellectual ranking of mathematics, it has struggled at times for visibility within STEM, as discussed in Section 8.1.2, with mathematics educators using language of risk and danger when discussing being drawn into STEM initiatives.

8.2.6 Summary

In this section, I have shown that all of the participants recognised the existence of disciplinary boundaries and I have demonstrated that the consequent negotiation of boundaries required when collaborating is challenging. Science educators, recognising that science is dependent on mathematics, can, in general, identify more potential gains from collaboration than can mathematics educators. For example, many participants believed that collaboration could help students to use mathematics more effectively within science. The type of gains suggested for mathematics are arguably less compelling and include science being an interesting context which might help with students' motivation. There is, however, limited evidence from research to support either suggested gain as an outcome of curricular collaboration.

I have demonstrated the contested nature of science, and indeed mathematics, in government policies. There was no consensus among participants as to whether, or to what extent, the mathematics curriculum – including content, sequencing and language – should be organised for the benefit of science. As mathematics is used within many curriculum subjects besides science, it is surely difficult to argue that science ought to have a privileged position in determining the mathematics curriculum.

Not all the participants saw a need for closer collaboration between mathematics and science. Some mathematicians even suggested that being seen as part of STEM could be dangerous for mathematics, with the domination of science within the government STEM initiatives (Wong *et al*., 2016) giving some credence to that view. Other mathematics educators cautioned that mathematics can get lost in interdisciplinary teaching.

The intellectual ranking of subjects was believed by some to act as a further barrier to collaboration. It was suggested by a mathematician that such elitism could lead to mathematicians holding themselves apart from others, and by a science educator that it could make getting support from mathematics colleagues in schools difficult for biology teachers. It is not clear whether and to what extent such elitist boundary structures actually exist or, if they do, whether they act against collaboration. There is thus an interesting oxymoron at the heart of the relationship between science and mathematics education in policy: mathematics is seen as elitist, but also as missing out to science and unappreciated within the STEM narrative and initiatives.

8.3 Policy

Fensham (2009) argued that in any discussion of policy one should ask whose values are favoured by a policy, which stakeholders have been successful in shaping a policy and which groups in society will be advantaged by the education practices flowing from the policy. In this section I will first ask whose priorities and values have shaped science education policy, and then which drivers are evident in determining the place of mathematics within science education policy. Finally, I will consider how government policy in science and mathematics education is asserted within schools, with a particular emphasis on how such assertions affect the relationship between school science and mathematics.

8.3.1 Policy making – whose priorities and values

The questions I asked the participants (the core questions are in Appendix 3) focused on policies ranging from the first national curriculum, over 25 years ago, to those being developed during the period of the interviews and which are now in place, such as the most recent national curriculum. In that period, influence has clearly changed as Ball (1990) argued. Nevertheless, it is possible to pick out periods of time when individuals and groups have had significant influence over policy making.

8.3.1.1 Individual influence: Sainsbury, Holman and triple science

MH argued that it is difficult to track influence in the policy sphere:

> *Impact is very difficult to assess and whether policy has worked out or not* […] *People like Ofqual and Glenys Stacey*[5] *over there may have had a far greater impact than we know and it's hard to pin that down.* [MH]

Ball and Junemann (2012) similarly concluded that it is difficult to trace influence through networks and, as such, policy making is frequently opaque. In spite of this opacity, two individuals stood out as being influential, particularly in STEM policy initiatives: Lord David Sainsbury, whose influence was commented on by seven respondents, and Professor Sir John Holman, whose name was mentioned by 12 respondents in connection with STEM, the National Curriculum and various other initiatives. David Sainsbury, Baron Sainsbury of Turville, was an unelected minister of science and innovation in the Labour government from 1998-2006 and wrote one of the six government reports on STEM education, '*The Race to the top*' (Sainsbury, 2007). Professor Sir John Holman was the government's National STEM Director and had previously worked for Sainsbury's charitable trust, Gatsby, as an advisor.

Seven respondents, including both science and mathematics educators, pointed to Sainsbury's influence on the STEM policies, for example:

> *Lord Sainsbury was probably the major influence when he was science minister, that's my impression* [He] *had a very long-standing interest in science and maths education,* [was] *in government* [and] *had a major influence on the emergence of STEM.* [SF]
>
> *There was a science S-E-T agenda* […] *Mainly championed by Lord Sainsbury.* [MC]

[5] Previously chief executive of Ofqual

None of the respondents suggested that Sainsbury's involvement was necessarily deleterious, but that it was considerable. SF was uneasy at the influence which Sainsbury, as an unelected single science minister, could have on education:

> *I mean what one notices, and it's really quite shocking, the way in which individual ministers have a really big influence over what happens over a particular period of time. And if you have Lord Sainsbury as science minister with a serious interest in STEM education then* […] *you can have a national agenda.* [SF]

In other words, the national STEM education policies were driven, at least initially, by someone who was unelected and not even in the Department for Education. EA suggested that the focus of the STEM initiatives on economic benefit came from Sainsbury:

> [The purpose of the STEM agenda] *was absolutely clear. It was crystal clear. And it was crystal clear in the minds of Gareth Roberts*[6] *and David Sainsbury. And it was about the business of economic benefit. Absolutely.* [EA]

For many respondents, John Holman was the personalisation of the national STEM initiatives; when asked about STEM they responded with what he had done. For example: '*Sir John Holman was the Director of STEM* […] *And so that personalised it'* [EA]. His previous work as an advisor for Sainsbury's Gatsby charity was suggested by some participants to have led directly to his appointment as national director for the STEM programme, being championed by Sainsbury: '*I think it's not a coincidence actually that John ended up with that position*' [SB].

Both Sainsbury and Holman emphasised triple science as part of the STEM initiatives. Triple science is the popular term for students studying separate sciences (biology, chemistry and physics) as three GCSEs, in contrast to double award or double science where the three sciences are taken as two GCSEs. Increase in triple science take-up was a key STEM priority, promoted by Sainsbury: 'The Government should continue its drive to increase the number of young people studying triple sciences' (Sainsbury, 2007, p. 6). The link between the push for triple sciences and STEM was clear in the minds of many participants, with some linking both to Holman. For example:

[6] Sir Gareth Roberts wrote the 2002 government report *Get SET for Success* which began the UK government STEM initiatives

> *It was the emerging STEM agenda that drove the move towards triple science. It was probably its biggest impact.* [SF]

> *STEM* [led to a] *big increase in the number of kids taking triple science, which I personally have serious worries about. It's one of the areas where I disagree with John* [Holman]. [SB]

A number of participants explained that the reason for the emphasis on triple science was to improve progression to A-levels, for example: '*progression to post 16 is most likely to come through triple science*' [SK]. Research by Homer, Ryder and Banner (2014) confirms that students who study triple science are more likely to progress to A-levels, although Bennett, Lubben, & Hampden-Thompson (2013) suggest that schools with greater curriculum diversity, in other words offering double, triple and perhaps a vocational science course, had higher progression rates than those who offer triple to all. Thus just offering triple science to all students is unlikely to improve progression. In spite of the link with progression, several of the science interviewees expressed disquiet about the re-emergence of triple science for two key reasons: reducing the breadth of study of those young people, as triple science would usually take 30 percent of curriculum time rather than 20 percent; and making it harder for people to do A-level sciences from double science. For example:

> *In theory A-level is meant to start building on the basis of double award science, but if you have got a lot of people who have done triple then they are inevitably going to be better prepared.* [SF]

SF further argued that the rise of triple science would tend to prevent those who had done double award from progressing to A-level, with the choice of double science at 14 (or even 13) thus becoming effectively an exit point for STEM careers. Bennett, Braund and Sharpe (2014) found that this was an early exit point in comparison to nations with higher STEM participation rates, who may have effective routes back in to STEM careers. It is problematic to have triple science as an entry requirement for A-level, and thus many STEM careers, as triple science is usually only permitted for those students who are anticipated to achieve high grades in the sciences, and Archer *et al*. argue that how students select, or are selected for, triple or double science is frequently not socially just. For example: 'Selective practices around Triple Science create and perpetuate social inequalities' (2016, p. 1).

8.3.1.2 Organisational influence

Both mathematics and science respondents felt that one consequence of the national STEM policies, and particularly of the High Level STEM Strategy Group, was that it allowed organisations a more direct influence on government policy than before. Some of this influence has continued and has led to ongoing access to decision making sites of government. SI here notes that those who have been involved with the STEM agenda have continued to have influence on government discussions and decisions, suggesting that the policy networks are still operational despite a change of government and a reduction in focus on STEM:

> *Charities particularly, and learned societies, having much better access to civil servants and government than we ever had before.* […] *Most of the bodies who've been involved in the STEM agenda in terms of doing things have access to* [government ministers] *in proper conversation and we have many, many conversations with the civil servants* […] *we are able now to have proper discussions and a lot of progress has been made as a result of that.* [SI]

However, as Millar (2014) has noted, many of the influential scientific bodies in England tend to prioritise science education for the minority group of those who are likely to continue to study science beyond school. Although he does not name the organisations to which he refers, it is likely that it includes some who are influential within the STEM policy network. It is difficult, to say the least, to deliver effective education for all based on the needs of an industry that will ultimately employ only a tiny proportion of each cohort. Indeed Hodson argued that subordinating the education of all 'to the perceived needs of the few who might study science at an advanced level' was 'ethically dubious' (1993, p. 93).

While working together in STEM may have had its difficulties, it almost certainly did mean that the messages had a higher impact than they would have done separately, as this former civil servant explains:

> *In many ways, the maths and science communities did, by coming together, by working together, I think did increase the strength and the impact of their lobbying.* [CSA]

Many of the respondents had been in the government's High Level STEM strategy group, which was not universally popular, in part because it was so big. However, MG recognised that it did have some value as it allowed openness and discussion of where the money available for STEM would be spent:

> *At least then there were mechanisms for talking together about the priorities of where the money was being spent in a fairly open way. Those mechanisms do not exist anymore, it is much more up to* [the] *whim* [of] *special advisors, ministers.* [MG]

This reduction in openness, and the consequent increase in the obscurity of policy making, was also discussed by other participants. For example:

> *This government* [Coalition Government of 2010-15] *is much more secretive about what it does than the previous one. So whereas before the agendas and minutes of the high level steering group on STEM, which was across both departments, BIS and DfE, were publically available, those are no longer available. In fact, it is only by hearsay that I know that the group still meets.* [MB]

> *Somebody like me, who's paid almost full time to be able to try and track it* [education policy] *can't track it, certain doors are closed* […] *We're also told there's a high level group that the ministers talk to and I've no idea who's on it.* [MH]

Thus organisations have more influence in policy making, but there is a concomitant increase in opacity such that influence is harder to ascertain.

8.3.2 Drivers in science education policy making: mathematics within science

From the interview data, I have identified a number of drivers in science education policy which have impacted on the position and amount of mathematics within science and thus the relationship between mathematics and science. Four of the drivers identified here lead to pressure for more mathematics in the science curriculum, the fifth leads to pressure for less mathematics in science. It is worth noting that there are minimal calls for a change in how much science is incorporated within mathematics.

8.3.2.1 Concern about standards

Over half the Interviewees noted broad concerns about falling standards across the curriculum, particularly in science. Concern about standards in state schools is not new. Indeed, the notion that: 'academic standards are in decline, particularly standards of literacy and numeracy' was identified by Ball (1990, p. 25) as a major discourse in education policy in the 1980s. That standards are still an over-riding concern was highlighted by CSA:

> *The main preoccupation of the Department* [for Education] *was around the basic standards of education, particularly in English and maths. And the importance of getting the general educational levels up. And that remains, I think, very much the department's focus.* [CSA]

Several respondents linked the content of the GCSE assessments to concern about standards. For example:

> *I have to say as a reviser at GCSE, there are moments when I bite my tongue and I am really quite shocked actually; some of the things that are graded at A and A*.* [SF]

Several respondents suggested the addition of more mathematics into the latest iteration of the science curriculum was a government response to the problem of standards. For example:

> *GCSE [science] standards have fallen, how can we make them rise, well, let's put maths in, because that's got to make them harder.* [MG]

However, some of the interviewees expressed conflicting feelings about the purpose of the additional mathematics. Many were broadly supportive of including more mathematics on the basis that much of science is quantitative, but some were uncertain that the way the government were going about it was necessarily helpful. SJ summed up this position:

> *If you think this* [addition of mathematics] *is going to beef up science and make it more respectable, I don't think that's a good reason. If what it's doing is helping teachers and therefore helping children to understand the value of when you need to be quantitative, then that's fine.* [SJ]

The notion that increasing the amount of mathematics will improve the rigour of school science is thus a key driver in the development of science curriculum policy. Whether the inclusion of more mathematics in science will prove productive, or otherwise, is not yet clear and neither is it clear if it will genuinely raise standards, whatever that means in reality.

8.3.2.2 STEM and the economic argument

Preoccupation with standards is closely related to concerns about international competitiveness and the prevailing political belief that education must serve the economy (Apple, 1993; Hill, 2013). The economic drivers behind education policy were widely acknowledged, particularly for the STEM initiatives; the majority of those interviewed stated that the reasons why STEM is promoted and was strongly funded by government are economic at heart. For example:

> [STEM] *is an economic priority that becomes an education priority as a result*. [SG]

> *From the point of view of the government* [STEM] *is about macro-economic policy. So it is driven by a thesis that says for an advanced country like this one our economic future lies in high-tech advanced technology, using the products of science, and in order to do that you need a technologically educated workforce. And therefore you need good people with qualifications in science and mathematics. And therefore you need to increase the popularity, particularly of those two subjects, science and mathematics. So that is the driver which has been the reason for this government being historically interested in* [STEM]*.* [SH]

In other words, the aim of education, or at least science and mathematics education, is to provide the ‘educational conditions believed necessary […] for increasing international competitiveness [and] profit’ (Apple, 1993, p. 4). Apple further argued that:

> A national curriculum may be seen as a device for accountability, to help us establish benchmarks so that parents can evaluate schools. But it also puts into motion a system in which children themselves will be ranked and ordered as never before. (*ibid*., p. 7)

SH’s identification of the need for ‘good people’ shows that this set of policies is aimed at those who will be likely to get high grades in science and mathematics qualifications, not at all students. The ranking and ordering of students allows these ‘good people’ to be recognised; such recognition is based on national curriculum tests and highly unlikely to be socially just (Apple, 1993). The perceived need for a supply of people to be part of a technologically educated workforce becomes a target to increase the numbers of students studying STEM subjects in post-compulsory education and thus a driver in science education policy. When asked about the aims, purpose and achievements of the STEM initiatives, three quarters of the respondents referred to an increase in numbers of students choosing to study A-level sciences and mathematics and, subsequently, STEM subjects at undergraduate level. For example, when asked to consider the success of STEM, SH commented that:

> [The] *headline measure for me was the numbers taking A-level maths and sciences. And I continue to think that that's the most important thing.* [SH]

CSA linked raising the standards of science education, the quality of science teaching and student numbers:

> *I think the key driver was to raise the standards of science education for all pupils, but particularly to ensure that science teaching was of a good enough quality and engaging enough to ensure that we had enough young people coming forward to do science and maths A-levels. And then going on to university to do degrees in science, engineering and maths.* [CSA]

In other words, science education needs to be good for all, but particularly good for those who might choose to continue with science, in order to encourage them to do so.

The economic argument and concomitant desire for an increase in student numbers has often been articulated by describing education as a supply pipeline; such arguments for education, while prevalent, do not always sit comfortably with those who are educators and teachers, as SG notes:

> *I'm not keen on the pipeline description; I don't think very many people who work in education are very keen on talking about pipelines.* [SG]

That there is, perhaps, a tension for educators between economic arguments and what might be seen as the educational ideal is also hinted at by this mathematics educator who had a prior career in business:

> *And [STEM] has got an economic* raison d'etre *at the end of the day because you're going to be competing in a fierce job market in a time of austerity and diminished economic prospects. It gives you a better chance. I don't mind that, I've been in business for half my career.* [MD]

Needing to specify that 'I don't mind that' suggests that MD has been in contact with plenty of people in education who do mind. The economic argument together with the view of education as a pipeline leads directly to a focus on those students who have a higher chance of becoming part of that pipeline. I previously identified a similar focus in STEM policies on such 'high status' students (Wong *et al*., 2016), which contrasts sharply with the teachers' beliefs (discussed in Chapter 7) in equity of provision and access for all, including those who are not going to become part of the pipeline of people with the qualifications required by employers.

8.3.2.3 Transition

In recent years, higher education institutions (particularly the Higher Education Academy) and the learned societies (acting through SCORE) have raised concerns about students' difficulties with transition from one level of education to another (see Chapter 3). Over half of the participants raised issues with transition; many of these concerns have focused on students' use of mathematics in other subjects including the sciences and engineering. For example:

> *The reason why folks seem to care about the maths content of science A-levels, very specifically A-levels, is the transition to higher education.* [EA]

The Walport Report to the government was focused on increasing numbers in post-compulsory science and mathematics education and on increasing opportunities 'for stretch and challenge for the most able learners' (Science and Learning Expert Group, 2010, p. 76). It specifically recommended that 'the mathematics content should be boosted substantially within 14-19 science education' and particularly that mathematics 'needed for progress in STEM beyond school/college' (*ibid*., p. 12). Minimum percentages of marks for mathematics in science qualifications (Ofqual, 2016), which had never been included in science qualifications previously, were introduced for all. SD suggested that the increase of mathematical content in science GCSEs had come directly from universities' concerns about undergraduates' use of mathematics, including in the biosciences:

> *What universities and biologists say about the subject* [is that] *students need to understand that it is a quantitative subject, it is not a purely descriptive subject* […]. *That has become putting an awful lot of* [mathematical] *content into GCSE sciences.* [SD]

Thus although the Walport report was focused on the 'most able learners', and universities' concerns are about undergraduates, mathematical content was added to science GCSEs which would be taken by all students.

8.3.2.4 Authentic science

One idea which recurred was that as science, or STEM, subjects are largely mathematical in nature, particularly in higher education and professional contexts, then so should they be mathematical in school in order to give an accurate or authentic idea to students about the nature of the subject, as the following quotes exemplify:

> *The STEM subjects are inherently mathematical. And as they are supposed to be a preparation for further study then where there is quite a lot of mathematics, particularly in physics, then if you don't introduce the fact that there is some mathematics at this stage then you're probably not giving people the right message about what they might expect when they come for further study.* [SA]

> *I'd certainly like to see more maths in the physics, to give it a more authentic feel* […] *The students are not well prepared for further study, they don't get an authentic feel of the subject.* [SI]

Concerns about authenticity which were raised focused, as in the two quotes above, entirely on future, rather than current, study. In other words, it is important that students who will continue to study the subjects have an authentic impression of science. Thus adding mathematics to science qualifications to make them 'authentic' is for the benefit of the minority of students who will progress to the next educational stage.

8.3.2.5 Qualitative and accessible science

This driver is distinct from the previous ones in that it is a call for less mathematics in science, or more qualitative science, partly in order to make science accessible to the whole cohort of students. There was acknowledgement from some science educator participants that the science curriculum and assessments had changed over time as a result of science now being studied by all students; all of those who mentioned this change were supportive of the idea of 'science for all'. For example:

> *If you read the Newsom report*[7] *you will see that nobody had a clue how to teach science to anybody other than in the grammar school cohort. Now our ambition is to teach worthwhile science and mathematics to everybody and that in a pretty undifferentiated way*. […] *We've gone for encouraging more people to progress with education than in the days of the grammar schools, and that affects the demands you can make on people.* [SF]

[7] The 1963 government-commissioned Newsom report was titled 'Half our future' and focused on the education of pupils aged 13 to 16 of 'average and less than average ability'

Part of this change has included less mathematics within science than might have been expected of the grammar school cohort, which was usually around 25 per cent of the school population:

> *There's been a de-mathematising of science. And it's been part of the move towards universal science education. So if you wound the clock back to the 1970s, science was essentially something that an elite did, both at A-level and at O-level, as it then was. When GCSE came in and when A-level moved from being something that 10 per cent of the population does to something that nearer to 50 per cent does, people looked for ways to make them more accessible to that wider ability group.* [SH]

That the reduction in mathematical content was deliberately done to make science more accessible can be seen in the claim from the NEAB examination board in the 1990s that: 'Candidates will not be prevented from demonstrating achievement in science by the use of […] mathematics which is excessively demanding' (quoted in Orton & Roper, 2000, p. 130).

For SF, it is likewise important that students experience success in doing science as it will lead to them finding it rewarding, particularly when it is compulsory for all.

> *My view* [is that it is] *better to do less and experience success than to do more and experience failure.* […] *Now, Michael Gove*[8] *will say no, if you lower the bar like that you cheat people, but the alternative view is that above all up to the age of 16 you must keep people engaged in education and feeling it's rewarding.* [SF]

In other words, as science is offered to all then it must be appropriate for all, even if some students might be capable of more. Science is unusual as a school subject in the way that the needs of students who may go on to further study are set against the needs of the majority (Osborne & Dillon, 2008).

SF agreed that there was less mathematics in science than in previous eras, and that was the correct consequence of science for all:

> *I wrote a piece* [in a journal] *pointing out how totally inappropriate* [Nuffield Chemistry] *was. And one of the things that made it inappropriate, it had 14 different types of calculation about amount of substance in moles. 14 different*

[8] Michael Gove was Secretary of State for Education from 2010-2014

> *types of calculation! And that was okay if you were at* […] *Grammar School* […] *but for the ordinary mortal it was crazy*. [SF]

Some respondents questioned the notion that students needed to have met mathematical ideas in mathematics lessons before using the concepts in science, arguing that a qualitative approach may be preferable at times in science. A call for a qualitative approach challenges the view held by some participants that adding in mathematics necessarily makes the science more 'authentic' or more 'rigorous' (as discussed above) and therefore that the removal of mathematics from the science curriculum must be avoided at all costs. SF argued that there is a case for ensuring that students have a qualitative understanding before introducing numbers, which could lead to an improved understanding of the science and consequently what the numbers actually represent.

> *A qualitative feeling for an explanation should precede the formulaic approach.* […] *You should teach more graphical and visual forms of data analysis, exploratory data analysis and the techniques of exploratory data analysis, before you get into the formality of the symbolic formulae.* [SF]

SJ agreed that it did not have to be the case that mathematics had to be the foundation subject which must be learnt before applying it in science, similarly challenging the view that science in school necessarily has to build on mathematical foundations:

> *This idea that maths is the foundation, you learn your numeracy and then your graphicacy and then you apply it in science.* […Instead] *you can go from jumping into something that's interesting and then tease out the fundamentals. That seemed to me to be lacking in a lot of the discussions between scientists and mathematicians, it was always the assumption that you needed to get the maths foundations sound first, rather than use the context of science and technology to say 'we really need maths to sort this out'.* [SJ]

SJ further gave the specific example of graph drawing to argue that you could understand what a graph is showing before you could write an algebraic equation to describe it:

> *Can we reverse this and say, right, well, we won't have the skill to understand what the equation of a line graph is, but at least you can get some sense, which is very important in science, of the relationship between two quantities; this gets bigger as that gets bigger. That is an easier idea than to write it down algebraically.* [SJ]

Such calls for a more qualitative approach in science, at least some of the time, challenges the idea that if students do not cover everything in a 'rigorous' mathematical way then it somehow undermines or misrepresents science, or that what they are doing is not properly science. A qualitative approach could be supportive of the mathematics curriculum if, as SJ suggests, it is used to point to the need for mathematics, although it is not entirely clear how this could realistically be achieved in school.

Other participants argued that science without mathematics is actually more difficult to understand. For example:

> [Without mathematics] *science is harder to understand because science, especially the physical sciences, are mathematical, and some of it can only be expressed in terms of mathematical models and laws.* [SH]

No one suggested at what point the amount of mathematics was correct. During the days of O-levels some science educators, including Shayer and Adey (1981), argued, from a Piagetian standpoint, that the cognitive demands of secondary science were too high and that the mathematics which was focused on was often not the most appropriate. Thus there were two related drivers to decrease the amount of mathematics in science GCSEs: the need for science to be appropriate for all and the belief that a qualitative approach can, and sometimes should, precede a quantitative approach to promote understanding of the science.

8.3.3 Assertion of policy: assessment and accountability measures

8.3.3.1 OFSTED and accountability

A number of participants noted that Ofsted inspections are not about collaborative working in schools, they are about teaching and external grades received by students in separate subject departments. Participants explained that collaboration is not recognised as evidence of successful practice by Ofsted and thus is not prioritised by schools. For example:

> *You have Ofsted coming for science and Ofsted coming for maths and they'll look for very different things* […] *The way that subject departments and teachers are assessed is about the subject, it's not about working together.* [MC]

> *There is so much emphasis on attainment in your own area, you've got to be confident in that first, so it's never going to be the top priority unless some of the achievement markers were specifically for* [a mutually supportive curriculum]. [SJ]

Other respondents agreed that collaboration is unlikely to be seen as a way to greater success for students in school departments. For example, SH asked why heads of department would look to work together:

> *What would incentivise them to* [work together]*? They are very powerfully driven by exam outcomes so what they want is lots of As in maths and lots of As in science. They won't necessarily see that the way to get the As in maths is by talking to the science people. That's a long-term outcome.* [SH]

The Royal Society Vision Report suggested that 'cross-departmental working and support' (2014, p. 79) between science and mathematics should be included as one of the metrics in an inspection and/or performance tables, although they were less clear what they anticipated that such work and support would look like or achieve.

8.3.3.2 Assessment

The combined effects of the competition between the three awarding organisations in England and the pressures on schools to achieve high grades were believed by many interviewees to be contributing to the reduction of mathematics in the science curriculum. The consequences of students not achieving high enough grades can be significant including additional inspections, moving down the schools' league tables and even being deemed inadequate and thus schools are very careful in their selection of awarding organisations and specifications. Some participants believed that the impetus to gain a greater share of the market was driving awarding bodies to minimise mathematical content of science qualifications, despite mathematics being in the specifications. For example:

> *We've sat around a table where representatives of awarding bodies[9] have openly said, we cannot put more mathematics in our GCSE because we will lose market. So, when you hear that, they're prepared to say that in a semi-public meeting, then that's telling you something, so I think that's the main reason* [for the reduction in mathematics within science]. [SI]

SI clearly suggests that awarding organisations believe that schools will back away from qualifications should the assessments contain a higher mathematical content. SA likewise relates the pressure on awarding organisations directly to schools' concerns about their performance:

[9] Awarding bodies are now known as awarding organisations (previously exam boards)

> *As a consequence, I think, of the awarding bodies seeking to maximise their market share, therefore trying to make their examination papers apparently easier so that more candidates get through. This helps with teachers of course because they need to get a higher percentage of pupils through so that the league table positions improve. So* [the reduction in mathematics within science] *is an unintended consequence of measuring schools' performance.* [SA]

While concerns about market share may well be true, there are other pressures on awarding organisations as many respondents acknowledged. Assessments need to be discriminating (effectively differentiating between grades), valid (accurately measuring what they are intended to measure) and reliable (producing stable and consistent results), without being over-long. SG suggested that science questions involving mathematics are avoided as they are not discriminating and described sitting in:

> *meetings where people have looked at science questions and said we can't have that maths in, it's too hard, students won't be able to do it. And therefore the question won't be a very discriminating question and therefore we* […] *shouldn't put that maths in because you'll either get 0 or 2.* [SG]

In other words, in a two mark question either students will be able to do it and will get two marks, or will not and will get none. If very few students get one mark then the question does not give the spread of marks required for a paper to be discriminating.

EA acknowledged that writing assessments is a challenging task as they cannot be predictable, and they must be both reliable and valid:

> *Keep*[ing] *the maths there and alive* […] *yet keeping the total assessment reliable and valid is really difficult actually, to be fair to the examiners, it's a really difficult task. And the casualty seems to have been the scope of mathematics which seems to have collapsed onto a relatively small number of topics dealt with in a relatively light way and every analysis has come to the same conclusion.* [EA]

By 'every analysis' EA is probably pointing to the SCORE reports (SCORE, 2009, 2012) and further notes that there are rules for what mathematics should be included in the science assessments but that a number of reports have found that the mathematics is not there. EA suggested:

> *It's not about the rules being wrong, I think folks just haven't adhered to the rules. Why it happens? Some folks will say it's competition and that's the obvious answer, but I'm not sure we have the evidence for it. The obvious accusation would be dumbing down and the race for the bottom, but I don't think we have any evidence for that. I think it's more that perfectly reasonable rules were written but folks found that they didn't have to adhere to them so they didn't.* [EA]

In other words the rules, the subject criteria, contained mathematics, but the awarding organisations found they need not include that mathematics within their papers and so did not. Orton and Roper had previously queried if there is a 'different, perhaps less mathematical, version of the subject being examined than is being taught? (2011, p. 146). SC, and others, pointed to Ofqual, whose role it is to ensure that assessments follow the rules, and suggested that the mathematics content had not been a priority for them:

> *And it may be the lack of proper oversight by Ofqual who should have been looking after this* […] *It's a terrible task. Essentially what they ought to be doing is monitoring every GCSE and key stage test that's around for its quality and for its adherence to the curriculum aims and the standards at which the different levels of achievement are set.* […] *Ofqual has no real bite, particularly at the subject level. They don't have enough subject expertise and they don't have enough staff.* [SI]

Several participants suggested the resultant effect of minimal mathematics in the assessments is, over time, minimal mathematics being taught within the science curriculum. For example:

> *And so there's less maths in the questions and therefore it perpetuates itself because teachers don't worry so much about it.* [SG]

> [Teachers] *look at the assessments and that's what determines what they teach: what is assessed. So, you can say that if mathematics has diminished, that's because the mathematics in the assessment has diminished.* [SI]

Thus while mathematics was undoubtedly in the criteria for the previous science GCSEs it may not have been in the assessments. Teachers study those assessments in deciding where to focus their teaching; less mathematics in the assessments will lead to less mathematics in the science classroom and therefore to less incentive for science to collaborate with mathematics.

8.3.4 Summary

In sum, as Ryder and Banner (2011) concluded, there are multiple aims identified in science education policy and such multiple aims create tension. Which aims are to the fore in policy making varies through time, as Ball (1990) and Williams (1962) identified. The relationship between mathematics and science, and the place of mathematics within science, changes according to the prevailing discourse in science education policy. When the key driver is to popularise science, or to push for the highest proportion of high grades, then the amount of mathematics within science seems to reduce. When the dominant discourse is the need to increase rigour or concerns about transition from one educational phase to another then mathematics is added to the science curriculum. Science is unusual in that the needs of those who will go on to further study are set against the needs of the majority (Osborne & Dillon, 2008). Recent education policy seems to be prioritising the apparent mathematical needs of those who may continue to study science in post-compulsory education over the needs of the majority. Higher mathematical content in the criteria will only lead to an increase in mathematics in science classrooms, however, if there is an attendant increase in mathematics in science assessments.

8.4 Transfer

Transfer has been conceptualised and described in different ways but is generally considered the use in one context of knowledge learned in another. There are a number of suggestions in the literature as to how students can be helped to transfer their learning; it is not viewed as straightforward by any authors who have seriously investigated it. Schwartz *et al*. (2005) suggest that transfer should be considered as preparation for future learning rather than the ability to recall facts and procedures. Some authors and educators still expect transfer of learning to be uncomplicated, however, and Osborne (2014) argues that the ‘vaccination’ view of mathematics teaching is widely held by science teachers.

8.4.1 Transfer: from science to mathematics

One of the reasons given for an increase in the mathematical content of the science curriculum is to improve students’ mathematics skills, as the following quote exemplifies:

> *Because mathematics is like a language or like music, you have to practice it. And if you’re only practicing it in maths lessons, it’s like learning a language and only practising it when you’re being taught French* [...] *And so by stripping maths out of*

> *science and geography and anywhere else it was to be found, you actually hit maths education as well as hitting science education*. [SH]

MA went further suggesting that reducing the amount of mathematics in science education had:

> *been absolutely fatal, I think, to both science and maths. Actually it's been a really bad move.* [MA]

There is, however, very limited evidence that using mathematics in science improves students' attainment in mathematics assessments. While few studies have explored transfer between mathematics and science, those which have do not demonstrate students linking their learning in the two domains. Bassok and Holyoak (1989) claim that aspects of mathematics learnt in physics do not transfer to mathematics and Zhang *et al.* (2015) concluded that students use different strategies to solve apparently similar mathematics and science items on the same test paper. Redish and Kuo (2015) perhaps help to explain why it might be difficult for students to transfer between the two as they argue that a different dialect, or a different-but-related language, of mathematics is used in physics than in mathematics itself. If improving students' mathematics is indeed a driver for increasing the proportion of mathematics in school science then there is an urgent need for further research to understand how students negotiate the boundary and transfer their knowledge between the two disciplines.

If, however, the mathematics in science is dealt with in a relatively superficial way then, no matter how much mathematics is put into science, it will be unlikely to support the development of students' mathematical understanding. About a third of the respondents, including both mathematics and science educators, expressed frustration at the way in which mathematics can be treated and taught in science lessons as the quotes below demonstrate.

ME bemoaned the lack of understanding required, arguing that science teachers want to get the mathematics done quickly to get it out of the way and get to the science, reflecting the complaints of some mathematics teachers in Chapter 7. ME suggests that more mathematics in science will only be a benefit to mathematics:

> *So long as those teachers who are teaching it can link it to those things being taught in the mathematics lessons.* [Otherwise] *the kids won't recognise that they are the same thing. And actually not only that but I think then that the mathematics*

> *content that is needed in science will be taught what I call 'by voodoo' – so it will be taught by rote rather than from a conceptual understanding because science teachers will want to get that done quickly in order to be able to get onto the science.* [ME]

MH agrees that there are science topics which could be used to teach mathematical ideas but often a 'trick' is used instead:

> *There's this classic triangle, which keeps coming up when you do speed, distance, time graphs or* […] *volume, density, mass and so on and it's always taught as sort of a rule or a trick. Whereas there's a core idea which encompasses all of these about proportionality and scaling and units and use of units.* [MH]

MC had recently discovered how quantitative topics tended to be taught in science and was not impressed:

> *I found out some horrifying things, actually, in terms of how science treats their mathematical topics* […] *I then discovered that science teachers do not actually, so I understood, do not actually use their science like Ohm's law or whatever it is, to help kids understand the algebra. As an example of manipulation of algebra. They use this triangle method and they put their thumb over.* [MC]

The teachers also raised the use of triangles to help students rearrange 3-part formulae and manage calculations (as discussed in Chapter 7). The majority of the mathematics teachers similarly argued that using triangles circumvents the need for mathematical understanding. SF likewise suggested that, at least for some of the mathematical content in science, students are taught how to apply a technique without really understanding what it means:

> *You could actually be taught to use a formula, substitute numbers in it and get the right answer without any real feeling for what the formula meant.* [SF]

Clearly, the benefit to mathematics understanding of an increase in quantitative content in science will be limited if that mathematics is treated as 'voodoo', 'magic' or a 'trick'; none of these approaches will help to develop students' mathematical thinking and understanding. Increasing the amount of mathematics in the science curriculum such that it is treated as a trick could be problematic and even impact negatively on student recruitment to A-levels and beyond. Boaler (2002), studying mathematics classrooms, found that many students talked about their dislike of mathematics not because of the cognitive demand of the subject but because the procedural teaching practices of the mathematics classroom left them no room for their own interpretation or agency. If the science curriculum really does tend to lead to the same requirement to surrender agency, then it could lead to students turning away from science rather than embracing it. Science educators could also learn from these findings and try to ensure that science students are not alienated during mathematical aspects of science through the limiting of opportunities for bringing their own interpretation and agency to bear in problem solving.

8.4.2 Transfer: the use of mathematics in science

Participants suggested that mathematics can be so embedded in science that it is hard to identify, making it harder for science colleagues to communicate with mathematics colleagues. SD recalled trying to list and then to discuss mathematical concepts in biology and finding it extremely demanding:

> *I do remember at the* […] *conference sitting down in a biology group with teachers and a couple of scientists, and our job was to discuss the mathematical concepts that were important in biology. And it was like getting blood out of a stone for all of us because we just hadn't thought like that before. I'm an ecologist by distant background so I'm aware I can do statistics, but I kind of think of it as ecology. You know, it's what I had to do to deal with the messy data from my fieldwork. I don't think of that as being the 'maths part' or the 'maths skills'.* [SD]

SD here suggests that scientists, or at least these biologists and biology educators, do not necessarily see the quantitative skills they use as mathematical skills, as they are so embedded in the scientific context, which would make discussing the links across school mathematics and science challenging.

SB, however, argues for a clear articulation of the mathematics in science to enable science teachers to communicate with mathematics colleagues in order to find out what students have covered, and further that if science educators want students to use mathematics in science then they cannot expect mathematics teachers to be 'helpers' for the science curriculum.

> *If scientists want kids to be able to do better mathematics* [in science] *then I think the practical difficulties of lining up what you need for your bit of science along with what they're teaching in their particular bit of mathematics are really quite severe. I*

> *suppose what would help the scientists is* […] *to be able to line up the science teaching curriculum with the maths teaching curriculum to know that any particular point that the kids are going to be fluent at some skills and where they are not. So I suppose it's about communication in that sense rather than expecting mathematicians to come in as sort of helpers.* [We need] *better communication* […] *a better articulation on the part of the science world of what's needed*. [SB]

Better communication sounds an excellent idea, such that one wonders why it has not happened thus far. Indeed, it is called for by many authors including Dodd and Bone, 1995, Orton and Roper, 2000, Osborne, 2011, Lyon, 2014, and Ross, Lakin, McKechnie and Baker, 2015, but is rare in school and, it would appear, in the policy realm. The ASE publication *'The Language of mathematics in science'* (Boohan, 2016) may be evidence of the wider science education community beginning to articulate exactly what mathematics is required in science. Teachers also expressed the need and advisability for science teachers to understand the mathematics curriculum, as discussed in Chapter 7. SH agrees that communication at school level is equally important, but very difficult to achieve:

> *So that, for example, you don't teach about chemical arithmetic until you've done ratios in mathematics. So that's about communication. Now you'd have thought that was rather easy – after all, all you've got to do is get the head of science to talk to the head of maths – but it is remarkably difficult.* [SH]

Even in the rare schools described in Chapters 6 and 7 where there was collaboration between science and mathematics departments, it was still unusual for the heads of science and mathematics to be in regular communication about the curriculum.

8.4.4 Summary

A number of participants, from both mathematics and science backgrounds, suggested that more mathematics in science could improve students' mathematics skills, and therefore that there ought to be an increase in mathematics within the science curriculum. There is no evidence in the literature to support such a supposition, which appears to rely on unsupported transfer from science to mathematics. Other respondents argued that as the mathematics in science is poorly treated, as 'voodoo' or a 'trick', then such an increase will not help students' mathematical development. As in Chapter 7, the triangle method was mentioned as a way of avoiding using the mathematics in science to promote students' mathematical thinking.

8.5 Summary

I have demonstrated that when looking at the interface of mathematics and science education policy it is, as Ball (2013) suggested, messy, confused and contradictory. In spite of the contradictory nature of policy making, there are a number of consistencies in the relationship between mathematics and science in education policy. Firstly, the relationship between mathematics and science curriculum policy has been consistently distant. From the initial development of the national curriculum, where the government pursued separate subjects rather than the notion of a whole curriculum of which the subjects were a part, mathematics and science curriculum policy have been developed largely independently. During the time of QCA there was more joined up thinking, although only one curriculum with explicit links was developed, and that had links from mathematics to science but not *vice versa*. The latest key stage four curricula were developed so independently from one another that they were even introduced in different years, with mathematics first examined in 2017 and science in 2018. The lack of collaboration in developing policy is echoed in its enforcement: Ofsted does not look at collaboration in school and it is not an achievement marker. Collaboration is a low priority in schools as a direct result.

There are wide-ranging concerns about the numbers of students choosing to take mathematics and the physical sciences in post-compulsory education. These concerns link to the enduring political belief that education exists to serve the economy and seem to conflict with teachers' belief in equality of opportunity.

There were concerns expressed that many students find mathematics difficult and sometimes dull and, perhaps unsurprisingly therefore, that those studying STEM subjects as undergraduates may similarly find mathematics difficult.

The amount of, and purpose for, mathematics in science qualifications has varied and been impacted on by these, and other, curriculum drivers. More mathematics within science is believed to make science more rigorous, more authentic, potentially to aid students' mathematical development, and to support students in the use of mathematics in further science study. All of these views are contested and there is very limited research evidence to support any of them.

Calls for closer collaboration at the policy level tend to be focused on the content and sequencing of the mathematics curriculum, and ensuring that it better supports the mathematics used within science. Unsurprisingly, many in the mathematics education community are resistant to such calls.

It can be challenging for the science education community even to articulate what mathematics is required within science. Doing so, particularly using the language of the mathematics curriculum, would be a good first step in promoting discussion and potential collaboration.

There is, moreover, an oxymoron at the heart of the relationship between mathematics and science. Mathematics is seen as the elite subject, with a higher intellectual ranking, but at the same time it has tended to lose out in STEM policy and funding, leaving mathematics educators wary of a closer relationship with science.

Chapter 9
Discussion

In the last three chapters I have described and explored the findings from the schools (Chapters 6 and 7) and from the policy makers (Chapter 8). In this chapter I discuss those findings in relation to the original research questions, namely:

1. How and to what extent can mathematics and science educators work together?
2. What are the barriers to effective, mutually beneficial, collaborations between mathematics and science teachers?
3. How might these barriers be addressed?

9.1 Practical barriers

There are practical reasons why science and mathematics departments tend not to work together. Practicalities restricting collaboration mentioned by respondents in this study included time, physical proximity and spacing of departments, timetabling, and setting and grouping. Other studies of collaboration have found similar practical barriers (for example: Hart *et al*., 1982; Venville, *et al*. 2002).

However, while teachers are stretched for time and have heavy workloads (Bloom, 2017), it is not at all clear that were they to have more time they would use it to collaborate with another department. While teacher workloads are currently very high, some of the contributors had been working in education since the 1960s and not one of them suggested that science and mathematics teachers had collaborated in some previous golden age. Thus, while time is certainly a factor, it is a very long way from being the only reason for lack of collaboration.

Having departments far apart from each other was mentioned by some policy makers as preventing collaboration, which is undoubtedly true if for no other reason than that it makes it less likely that teachers will know staff in the other department. It was noticeable that in four of the schools (Beebury, Ceeton, Eyston and Effdon) the close proximity of departments was a factor in promoting collaborative efforts, and moving departments to be near each other was an action taken by some senior leadership teams to promote collaboration. However, close proximity in itself does not guarantee that departments will work together.

Timetabling was raised as a factor which could facilitate or hinder joint project work, but was not seen as a barrier to other types of collaboration. However, a key obstacle, mentioned in four schools (Ayford, Ceeton, Deecom and Effdon) was that of different sets and groups for science and mathematics. Setting was an issue for organisational reasons with projects, but it will be discussed later (Section 9.4.3) as the implications run deeper than the straightforwardly practical.

The practical reasons put together suggest that they are not the full answer to why science and mathematics departments rarely collaborate. In this study I have brought a variety of theories to bear on the findings which has allowed a more detailed and nuanced picture to emerge of the constraints to collaboration.

9.2 Bernstein, power and boundaries

As discussed in Chapters 4, 7 and 8, Bernstein argues that ‘A can only be A if it can separate itself from B’ (2000, p. 6). To achieve such separation requires boundaries around the separate entities, in this case around school subjects or departments. The impact of boundaries on the relationship between mathematics and science is visible all through the data, in both the collaborating schools and the interviews with the policy makers. Strong classification and thus strong insulation between departments demands that subjects are kept apart (Bernstein, 2000) and there are some benefits in so doing. For example, it allows the creation of strong department teams often with team rooms which can be a nurturing place, particularly for early career teachers (Burn, Childs, & McNicholl, 2007). Breaking down the barriers between departments could lead to a weakening of the often valued relationships within subject teams. While the boundaries are socially produced rather than physical, they are not easy to cross and Newman cautions that:

> From the moment they are established, there are always groups who have an interest in finding ways to move beyond the barrier [...] But crossing the border does not always bring the expected benefits. (Newman, 2003, p. 14)

It is worth considering who is pushing for the boundaries to be crossed, what the expected benefits are to crossing the boundary between mathematics and science and whether those benefits are achieved in reality.

9.2.2 Hierarchy and decision making

A number of authors suggest that departments should work together (for example, in the UK focussed literature: Dodd & Bone, 1995; Orton & Roper, 2000; Osborne, 2011; Scott, 2012; Lyon, 2014; Ross, Lakin, McKechnie, & Baker, 2015) and my initial assumption was that any such work would be led by heads of department. I was surprised to find that in only one of the schools (Eyston) was the collaboration actually led by the departmental heads. What was clear was that support, at the very least, and often compulsion, from the senior leadership team was essential to the initiation and continuation of collaboration and border crossing. The importance of senior leadership encouragement was likewise recognised by some of the policy makers, for example:

> *What would incentivise a head of maths to sit down* […] *with the head of science and their teams to really make sure that things coordinate?* […] *Because it won't be top of their agendas. Because they are in a box that's called 'I am science,' 'I am maths.' It's the job of the curriculum leaders, the headteacher, to make it happen, kicking and screaming if necessary.* [SH]

SH here recognises the importance of the senior leaders and the headteacher in bringing together the heads of department. SH also recognises that there are significant barriers to be overcome, described here firstly as science and maths being in separate boxes and then as kicking and screaming to avoid talking, suggesting that SH believes that the majority of heads of science and mathematics will not want to coordinate their curricula. If the heads of department are so reluctant, then the senior leadership team would need to be convinced of significant benefit to collaboration to push for it, as usually matters of curriculum are left in the hands of heads of department (Ball, 1987). The central role of the headteacher is often not discussed in studies of collaboration, although Straw, MacLeod, & Hart, 2012, found that senior leadership support was key to successful STEM collaboration.

One way that headteachers and senior leaders encouraged collaboration was in the creation of a joint faculty of science and mathematics. There were joint faculties in Beebury (also with technology), Ceeton (also with design technology and physical education) and Eyston. In a study from the early 1980s, the authors similarly found that the creation of a mathematics-science faculty was a contributing factor towards the success of collaboration (Hart, Turner, & Booth, 1982). They also suggest that collaboration is more likely to be possible in a new school as there are no entrenched positions. It is, therefore, perhaps significant that two of the schools in this study were new schools, or at least new builds: Beebury and Ceeton.

9.3 Asymmetric dependency

Science is dependent on mathematics. The extent of that dependency and exactly which mathematics is depended on varies across the different branches of science, but the fundamental fact of that dependency is not seriously challenged, as discussed in Chapter 1. The converse is not true; mathematics is not dependent on science. There is, thus, what I term 'asymmetric dependency', with science more dependent on mathematics than *vice versa*, which does not appear to be discussed in the literature but which has several significant effects on the relationship between mathematics and science.

9.3.1 Greater benefit for science

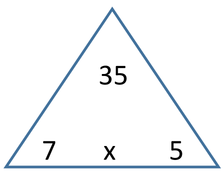
Bernstein (2000) argues that when the degree of insulation changes between categories one should ask who benefits. Asking this question allows us to see the first effect of the asymmetric dependency: that science will tend to benefit more from collaboration and a closer working relationship than will mathematics. Students need to be able to use and apply mathematics in science; they do not need to be able to use and apply science in mathematics. In the GCSE criteria, for example, there are aspects of mathematics listed for every segment of the science curriculum (DfE, 2015), but there is virtually no mention of science in the mathematics curriculum (DfE, 2013d). Up to 30 percent of marks in GCSE science assessments will come from mathematics (Ofqual, 2015), but there is no requirement that there will be science in the mathematics paper. While some of the content of the mathematics curriculum is used within science, there are large portions of the content of GCSE mathematics which are not and thus any alignment of teaching strategies is likely to benefit science more broadly and profoundly than it benefits mathematics.

Thus, while for science educators it is obvious that collaboration with mathematics would potentially be beneficial, mathematics educators do not have the same view. MG, who had previously worked in science education, explained that *'when you sit in science, you see maths education strongly overlapping with science education'* but that in mathematics you also have important links to other disciplines such as social sciences and vocational mathematics that science educators are, in general, unaware of. MG continued: '*your Venn diagrams look different*', in other words what you see as the area of overlap is just not the same.

For the relationship to be mutually beneficial, mathematics education would need to gain approximately equally from the collaboration. It is worth considering under what circumstances that would be the case. As science includes significant mathematics, it has been suggested (for example by Fairbrother, 2008) that science teachers could use quantitative science to support students' mathematical development, effectively increasing the amount of mathematics teaching that students receive. While there are differences in language and focus between the disciplines, which complicate this argument and will be discussed later, a number of both mathematics teachers and policy makers in this study suggested that science did not, in general, 'treat its maths well'. For example MC:

> *I found out some horrifying things, actually, in terms of how science treats their mathematical topics* […] *science teachers do not actually use their science* […] *to help kids understand the algebra.* [MC]

Mathematics teachers and educators also pointed to science teachers employing 'magic', or 'tricks' when using mathematics within science, meaning that students' mathematical development was not being supported, even though there was mathematics within the science curriculum. For instance, the triangle is an interesting example of a pedagogical technique which is held in aversion by many mathematics educators who are concerned that they are essentially a way to circumvent mathematical thinking. As triangles are often used and appreciated by students in science they are crossing the boundary into mathematics teaching. Triangles have recently begun to be seen in primary mathematics, where they are often known as 'fact family triangles', as a way of teaching children about the relationship between multiplication and division. For example:



If primary school pupils become familiar with the triangle as a way of representing the manipulation of 3 part equations then it is likely that they will use them in both science and mathematics at secondary school.

Research has shown that children find proportional reasoning very difficult and that 'children seem to have significant difficulty in understanding intensive [per] quantities' (Nunes & Bryant, 2015, p. 751) of which there are, of course, many in science and:

> connecting these with numerical representations is problematic […] Research showed that when pictorial representations of problems were used children did better than when numerical representations were used. (*ibid.*)

Perhaps the triangle could be considered a pictorial representation of a proportional reasoning problem which helps students to understand; perhaps it is a ‘trick’ which avoids the requirement for mathematical understanding. Exactly which it is should perhaps be the focus of further research and may well be different depending on how it is used by individual teachers.

Furthermore, there was concern from some mathematics policy makers that the subject can get ‘lost’ when it is integrated with science, in other words it can be side-lined or under-emphasised. Becker and Park (2011), in a meta-analysis of integrated STEM teaching, found that mathematics tended to have a smaller, or even a negative, effect size compared to other STEM disciplines. In other words, mathematics attainment can be lower when it is taught combined with other STEM disciplines than it is when taught separately. Concerns with mathematics particularly (but also science) achievement in GCSEs were behind the decision at Beebury to reduce the amount of their integrated teaching in key stage 3.

The question must surely arise as to the reason for these negative effect sizes; Becker and Park themselves do not suggest why they occur. One reason could be mathematics getting ‘lost’ as the participants in this study suggested. Pang and Good (2000) analysed a number of integrated science and mathematics resources and found that they were more commonly science than mathematics focused. Frykholm and Glassom (2005) asked their pre-service teachers to write integrated teaching units and similarly observed that the units produced, even by a mix of mathematics and science majors, tended to be science-focused. With science the focus of the planning, perhaps it also becomes the focus for the teaching and consequently the learning.

There may, however, be another reason why the mathematics attainment tends to be lower in joint projects. Redish and Kuo (2015) argue that maths-in-physics is a different-but-related language to that of pure mathematics at undergraduate level; that physicists use mathematics differently to the way that pure mathematicians do due to the focus of physicists on the phenomena being studied, compared to the mathematicians’ focus on pattern. I have similarly argued (Wong, 2017) that graphs are used differently at school level in mathematics and science, related to the different epistemology of each discipline. If mathematics is integrated into science, which mathematics is prioritised: mathematics as taught by mathematics departments, or mathematics in science? If the differences identified by Redish and Kuo are as significant at school level as they are at university level then using maths-in-science type mathematics in a joint lesson will be less likely to lead to learning of maths-in-maths – and consequently this may also go some way to explaining the lower effect sizes. The only school in this study which focused on how mathematics is used differently (rather than taught differently) in mathematics itself and in science was Ayford; the need to emphasise such differences was not prioritised in the other schools.

For there to be a mutually supportive curriculum the use of 'tricks' would need to be replaced with strategies designed to promote mathematical thinking and reasoning in science. For example, in teaching speed = distance/time, science teachers could emphasise the proportional reasoning required to understand how speed varies with distance and time rather than relying on the triangle to rearrange the equation and get a numerical answer quickly. Indeed, Osborne (2014) argues that engaging in such mathematical thinking is essential when learning science.

9.3.2 Maths blame

The second effect of the asymmetry of dependency is that of frustration and blame. Many of the teachers interviewed expressed frustration that the 'other' subject did not provide much support for theirs. Mathematics teachers (Section 9.3.1) believed that the science curriculum and science teaching should better promote mathematical thinking; science teachers expressed frustration that students had not covered the mathematics needed for science either at all or in sufficient detail. Most of the science teachers interviewed who were aware of what students had, and had not, covered in mathematics cited the collaboration as a source of that knowledge. They were, in consequence, actively ensuring any necessary mathematics was covered in science. Osborne suggests that this acceptance of responsibility for students' mathematical knowledge may be unusual among science teachers:

> Many [science teachers], perhaps, operate with the vaccination model of mathematics […] that it is not their responsibility to educate students in the mathematics […] required to understand science. And if students have not been vaccinated, there is little that they, the teacher, can do. (Osborne, 2014, p. 187)

In other words, science teachers expect students to have the mathematical knowledge they need when they arrive in the science lab and do not do much about it if they do not.

Although this sounds like rather an unlikely abdication of responsibility, a similar conclusion was reached by the AKSIS project team:

> Many teachers we interviewed recognised the difficulties that pupils had with graphs, but few had made a point of teaching pupils about the construction and use of graphs. (Goldsworthy, Watson, & Wood-Robinson, 1999, p. 2)

Science teachers, it would seem, often expect students to be able to use mathematics within science, recognise that they struggle to do so and do little about it, although it is widely recognised that students find it hard to transfer their learning:

> Teachers have long been concerned about the difficulties their students experience when transferring what they learn in their mathematics lessons into the science classroom. (Needham, 2016, p. 14)

When students struggle to transfer their knowledge smoothly and without help, science teachers may blame their mathematics colleagues for students' deficiencies. This blame can be identified even (and perhaps especially) when students have not yet covered the mathematics that science teachers are expecting. The prevalent idea that students' difficulties in using mathematics in a scientific context can be attributed to their prior, and in some way deficient, mathematical education I articulate as *'maths blame'*. Blame, according to the Oxford English Dictionary, is: an expression of disapprobation; the imputation of demerit on account of a fault or blemish; a charge or accusation; the responsibility for anything wrong. It is also a verb, for example: to lay the blame on; to fix the responsibility upon; to make answerable; to find fault with or censure (OED, n.d.).

Such blame sounds extreme and perhaps unlikely, but it can also be identified in the literature. A number of authors have asserted that school students' problems with mathematics in science are due to inadequacies with mathematics teaching. For example, Scott blames students' problems with mole calculations on mathematics teaching and claims an:

> algorithmic approach to mathematics teaching hinders problem solving ability in other subjects, most notably in the sciences. This is a […] challenging issue to solve in which the action to be taken would be in the mathematics classroom rather than the science classroom. An improved communication between science departments and mathematics departments will be important in solving this problem. (Scott, 2012, p. 336)

Here Scott demonstrates Osborne's identified belief that if students have not been vaccinated there is little the science teacher can do: he suggests any action to be taken should be within mathematics teaching not within science lessons. He further claims that collaboration and communication between mathematics and science will be the key to solving the problem. Quite how this might work is not explained – perhaps it might involve science teachers telling mathematics teachers how they could better do their job.

Blaming 'other' colleagues is a convenient way of avoiding taking responsibility oneself for ensuring that students can understand the mathematics required in the science classroom. Mathematics teachers interviewed had experienced and even expected 'maths blame' from some science colleagues. If collaboration is approached as suggested by Scott (2012) above, in other words, science teachers telling mathematics teachers how they should teach to support science, then it is highly unlikely to be successful or productive, particularly when the over-riding atmosphere between departments is one of blame and censure.

Maths blame links directly to the asymmetric dependency between science and mathematics. Science and science education are dependent on mathematics such that difficulties with mathematics can significantly hinder learning in science, as discussed in Chapter 7. The asymmetric dependency is also the reason why the contrasting science blame was not in evidence anywhere in the data. Mathematics teachers were frustrated by some of the ways in which science teachers dealt with mathematics, but their teaching methods were not believed to have a direct impact on whether or not students could access the mathematics curriculum in the way that mathematics teaching was believed to impact science learning.

9.3.3 Curriculum ownership

The dependency of science on mathematics raises the question of ownership of the curriculum and thus who should control the content and sequencing of the mathematics curriculum. Should it be solely mathematics educators who make those decisions, or should the needs of science be taken into account? And if so how and to what extent? Bernstein (2000) argues that there is selection informed by ideology in how one discipline 'is to be related to other subjects, and in its sequencing and pacing' (Bernstein, 2000, p. 34). The dependency of science on mathematics can lead to science educators believing that they should have some say in the content and sequencing of the mathematics curriculum, as demonstrated in the data in Chapter 8 and also in the quote from Scott (2012) above.

Teachers in the schools cited government policy such as very disparate curricula, assessments and Ofsted inspections as a limitation to their collaboration. Using the policy makers' data (Chapter 8), I showed that teachers' perception of the curricula as being pursued entirely separately from each other, with minimal collaboration between the writers of each, was broadly correct.

Many mathematics educators resisted the idea that science should have any say in the mathematics curriculum. Both mathematics policy makers and teachers raised the contested idea of mathematics as a service subject (Hoyles, Newman, & Noss, 2001) and, while most accepted that it was a service subject, at least to some extent, the majority resisted pressure from science to dictate the mathematics curriculum. Science was dominant in STEM policy making (Wong *et al*., 2016) and therefore it is perhaps understandable that mathematics educators are wary about the potential for science to influence or dominate decisions regarding the mathematics curriculum.

The disparate nature of the two curricula therefore limits the utility of collaboration between the subjects, through limiting the extent to which they are likely to be able to be supportive of each other. The lack of support appears to cause frustration in both directions. Yet having more correlated National Curricula, even if desirable, would not completely ensure that mathematics and science were supportive of each other. The secondary curriculum is organised as two key stages with content specified by key stage and thus in two or three year blocks. To organise the teaching of mathematics to support science, or science such that the necessary mathematics has already been taught, would still require discussion or collaboration locally within schools.

9.4 Transfer

9.4.1 Science context

What goes on in mathematics lessons may also not be the whole reason for students' difficulties using mathematics in science. To use in one subject knowledge acquired in another is recognised as challenging by every author who has seriously studied the issue. Additionally, Barnett and Ceci (2002) argue that during transfer, knowledge of the context being transferred *to* is important, as well as the knowledge being transferred. Indeed, science teachers appreciate that the same piece of mathematics can have different levels of challenge in different scientific contexts. For example, the majority of students will understand fairly intuitively the relationship between speed, distance and time as they will have travelled in a variety of ways, seen speed limits on the roadside and experienced how much longer a familiar journey takes in heavy traffic or when walking rather than driving. This everyday experience with the phenomena in question makes teaching the both the understanding and the calculation of speed, distance and time relatively straightforward.

The calculation of amount of substance is mathematically very similar, involving a three-part equation:

$n = m/M$ or amount of substance (number of moles) = mass ÷ molar mass.

There are, however, three definitions of 'the mole', causing confusion for teachers as well as students (Kind, 2004), and students will not have direct experience of 'the mole' or molar mass in the way that they will have experience of speed or time. Thus while both involve intensive quantities (those which include 'per' such as miles per hour or mass per unit area), known to be difficult for many students to grasp (Lamon, 2010), the familiar context makes it far easier for students to apply proportional reasoning to speed than moles. There are 14 three-part equations of the type $a = b \times c$ in the physics section alone of the Combined Science GCSE (13 in the foundation level paper) (DfE, 2015), many in contexts which will, like moles, be experientially unfamiliar to students. Students are expected to recall and apply each using SI units. It is, therefore, perhaps understandable that many science teachers choose to use the triangle, denounced as a trick by many mathematics educators, to help students to navigate through the mathematics required rather than try to teach proportional reasoning in 14 different, challenging and often unfamiliar contexts.

Using the lens of transfer demonstrates that the expectation of frictionless transfer from mathematics to science is naïve. Students need help to use mathematics in science, particularly where the scientific context is unfamiliar to them.

9.4.2 Language and use of mathematics

The differences in language show a strong classification of discourse which Bernstein (2000) argues is likely to lead empirically to a dislocation in the transmission of knowledge. Newman argues that:

> Crossing the language barrier of the borders between academic disciplines […] is often harder than the trans-boundary movement which is increasingly taking place across the borders between states and regions. (Newman, 2003, p. 16)

Indeed, the language barrier was identified by teachers as significant in limiting discourse between mathematics and science teachers as well as being extremely challenging for students to cross. ESL suggested that the language boundary is demanding and that teachers are critical in helping students to cross it:

> *Mathematical language is part of the difficulty, I think, of children understanding mathematical skills* [in science]*. Sometimes they just don't understand the word you're using and when you demonstrate they say, 'Oh yes, I understand what you've got to do'.* [ESL]

Redish and Kuo (2015) argue that maths-in-physics is a different but related language to maths as used in academic mathematics as physics, together with the other physical sciences, uses knowledge of physical systems in constructing and using mathematical manipulations. They suggest that part of the 'acculturation of a physics student is learning to interpret the math physically, not to only focus on mathematical structure and manipulations' (2015, p. 567).

If they are correct and mathematics is used differently in science to how it is used in mathematics classrooms then this provides further evidence that simply expecting students to use mathematics in science without assistance is naïve and unrealistic. Using the mathematics physically, to learn to interpret what the results mean and to apply that meaning to a physical (or indeed biological) system, is important in science. I have similarly demonstrated (Wong, 2017) that graphs are used differently in the two disciplines, meaning there is a need for students to be taught specifically how to construct and use graphs in science, in a scientific way, rather than relying rather hopefully on transfer from mathematics. Leinhardt *et al*. (1990) suggest that 'real-world' contexts in mathematics do not necessarily support the learning process in mathematics; in science it is very different, or even the reverse, as graphs are an aid to understanding the phenomena being investigated through being representations of observations and aiding the detection of underlying patterns. Science teachers, therefore, need to teach students how to use mathematics in science and to accept that the responsibility for so doing cannot be outsourced to the mathematics department.

9.4.3 Transfer and setting

Many authors acknowledge that there is a need for the teacher in the subject to which learning is transferred to help students to make the bridge between prior and new learning. Schwartz *et al*. (2005) argue that prior knowledge is better considered as 'preparation for future learning' than facts and procedures which can be easily recalled and applied in a new context. Larsen-Freeman (2013) explains bridging between prior and new learning as the need to 'transform' learning in the new context and Rebello *et al.* (2005) as the need for students to be helped to 'reconstruct' their learning in the transfer context. Reconstructing can be apparently simple – a few minutes spent in recapping prior mathematics learning within science lessons. At Eyston, although teachers suggested one of the key reasons to collaborate was to save time in an overcrowded curriculum, they do not expect students to transfer their learning without being supported to do so; saving time does not mean never needing to help students to use their mathematics in science. Teachers used recaps of mathematics learning in science, but an effective recap requires that science teachers know what students have covered in mathematics, when and how.

However, in many schools, students are set differently in mathematics to how they are set in science. Furthermore, not all mathematics teachers will teach the same way and not all teachers will even teach all their classes in the same way, so if science teachers are looking for 'the' way that their students are taught a piece of mathematics they are searching for a chimera. Thus differentiation and the individualisation of learning, often for completely valid and appropriate reasons, can act as a significant barrier to science teachers helping students to transfer their mathematics learning. It could also potentially add to science teacher frustration as they try to understand the teaching methods used in mathematics in order to be able to help their students. Only at Eyston (a very small independent school) had there been any attempt to harmonise teaching across mathematics, let alone across mathematics and science, and even there they kept such harmonisation to a minimum, acknowledging that it restricted teachers' freedom, and thus professional agency.

Schools, therefore, have to choose between having a 'set' way in which a mathematical topic is taught, which restricts teachers' professional agency, and giving teachers freedom, which makes it harder for science teachers to understand how mathematics is taught. Most choose to give their teachers freedom, which in consequence makes it much harder for science teachers to support transfer from mathematics. Adding further complications are the latest GCSE criteria which state that mathematics in science GCSEs should be at 'levels up to, but not beyond, the requirements specified in GCSE mathematics for the appropriate tier' (Department for Education, 2015). This statement appears to implicitly assume that students entered for higher tier in science will necessarily be entered for higher tier in mathematics, which may not be the case. One could argue that it also implicitly assumes that students will transfer their learning from mathematics to science, particularly as there is already detailed mathematical content embedded within the science curriculum (DfE, 2015).

Thus differences in setting and grouping were a significant, and perhaps surprising, barrier to several types of collaboration including project work and attempts to provide more united or harmonised curricula. Setting is not a straightforward barrier to overcome as any attempt to harmonise curricula necessarily reduces the agency and control of the department, the individual teacher, or both, to organise and teach their students as they believe best in their professional judgement. The complexities of collaborating with different setting arrangements are not foregrounded in published research on mathematics-science collaboration, yet I have found that different setting is a critical barrier acting against collaboration in a number of ways.

9.4.4 Seeing connections

Some authors such as Zhang *et al.* (2015) suggest that it should be relatively easy for teachers to find points of overlap in the content of mathematics and science. This presupposition is also evident in the rationales for mathematics and science to work together identified by Pang and Good (2000) in their review of studies of integration. The rationales included that mathematics and science are both attempts to discover patterns and relationships, they share similar scientific processes, they should be connected to real life situations and authentic problems, and both require quantitative reasoning. With so many apparent similarities reported it is understandable that authors would assume that finding points of overlap would be undemanding. However, none of the participants in this study found making connections across the subjects straightforward (as discussed in Chapters 6 and 7). While it might be tempting to assume that therefore these teachers are not particularly effective or that the science teachers are not very numerate, that would simply not be the case. All the teachers were experienced, were working across department boundaries and were apparently highly regarded within their schools. A deficit model of the teachers is therefore not appropriate.

Perhaps the problem is not with the teachers, but rather with the presupposition. Suggesting it is relatively easy for teachers to find points of overlap presupposes that teachers are able to see connections between the disciplines, when to do so would require content knowledge of both subjects and an understanding of the connections both within and between them. Having the knowledge and appreciating the connections is recognised as being demanding and evidence of expert practice in just one of the subjects (Turner & Rowland, 2011); seeing connections across two disciplines when the teacher probably teaches in only one is clearly not as simple as many authors apparently assume. The difficulties with finding connections were related to concerns about the context of several of the joint projects and the rigour of the science and mathematics which was covered in them (Chapter 6); rigour of projects was likewise identified as a teacher concern by Venville *et al*. (2002). Teachers having difficulty in seeing connections and finding suitable points of overlap between the subjects is thus a significant barrier acting against collaboration and is not easily overcome.

9.5 Social justice

When I began this study I did not imagine that the relationship between school science and mathematics education would have a social justice dimension. However, as noted by Ball (1987), Goodson (1995) and others, not all subjects in schools have equal status. According to Goodson, 'the close connection between academic status and resources is a fundamental feature of our educational system' (1995, p. 173). Subjects with high status, which includes mathematics and the physical sciences (Wong *et al*., 2016), are more likely to attract high status students, who are those anticipated to achieve high grades in GCSE examinations. Ball (1987) argues that departments in school fight between themselves like mediaeval barons for territory and power and that partly what they are fighting for is access to those highest status students, particularly post-16. Science and mathematics departments are, of course, often competing for these same students, adding further tension to the relationship. There can, however, be alliances between the departments in recognition that many of those who study science will also choose mathematics. For example, in Ayford, one aspect of their collaboration was a joint year 11 and 12, joint mathematics and physics lesson to encourage students to consider studying both mathematics and physics at A-level.

A large number of the policy participants noted that the STEM policies were enacted for economic reasons and the belief that higher numbers of students studying science is good for the country as a whole. Jenkins accepts that this belief is widespread, but nonetheless challenges the assumption arguing that:

> The link between science education and economic development is, of course, far from straightforward [although] the link is [used to] justify the reform of school science education. (Jenkins, 2009, p. 81)

He further argues that such a view has consequences for school science education in directing the objectives of the curriculum 'towards the production of an adequate number of well-qualified scientific personnel' (*ibid*.). Such aims have significant consequences for social justice and the pursuit of science for all students.

9.5.1 Authentic science

A number of the policy makers suggested that school science should aim to be 'authentic' to give an accurate impression of science. While having science in school being 'authentic' initially sounds like a worthwhile ambition, there are two problems with having this as an ideology driving curriculum policy. The first is that it ignores the fact that school science is not, and never can be, the same as 'authentic science', even if there were an agreed definition for the nature of science. Bernstein (2000) argues that there is a gap between the pedagogic discourse of, for example, physics, and the activities in the field of production of that discourse (in other words, doing physics). They are not the same; school physics is not 'real' physics. As the discourse of physics is therefore necessarily moved from its original site to its new positioning as a pedagogic discourse, there is a transformation and this transformation is driven by ideology. Bernstein further argues that 'no discourse ever moves without ideology at play' (Bernstein, 2000, p. 32).

Watson recognised the distinction between mathematics as a discipline and school mathematics, arguing that school mathematics has 'different warrants, authorities, forms of reasoning, core activities, purposes and unifying concepts' (2008, p. 3). The same is true for school science: it thus is not, and cannot be, a subset of the discourse of science. Furthermore, even the idea of 'school science' is a questionable construct, according to Jenkins, as it 'ignores important philosophical, conceptual, and methodological differences between the basic scientific disciplines' (2007, p. 265).

Therefore, holding that school science must be 'authentic' is an ideological position which can inform and drive the transformation of the discipline into pedagogic discourse and drive the content, pacing and how science is related to other subjects, including mathematics. Several of the policy maker participants suggested that science should be more mathematical to give an authentic feel to the subject. Osborne similarly argued that: 'if mathematics is not a core feature of what happens in science classrooms the nature of science will be misrepresented' (Osborne, 2014, p. 187). Such a view was, however, far less prevalent among teachers, particularly science teachers.

The second problem with having 'authentic' science as an aim is that it tends to lead to the needs of those who will go on to further study being prioritised. It is they who need to be given the authentic experience, to be shown what the subject is properly like, so that they know what they are choosing when they continue studying. None of the interviewees suggested that those who would stop studying science needed an authentic view of the subject but several related the need for authentic science to concerns about transition and student numbers.

The perceived needs of those who will continue to study science thus seem to be taking priority over the needs of the majority – a position decried as 'ethically dubious' (Hodson, 1993, p. 93). The ethical issue can be summarised as follows:

> The problem with framing the discussion about school science in terms of the supply of the next generation of scientists is that it defines the primary goal of science education as a pipeline, albeit leaky. In so doing, it places a responsibility on school science education that no other curriculum subject shares. Our view is that a science education for all can only be justified if it offers something of universal value for all rather than the minority who will become future scientists. (Osborne & Dillon, 2008, p. 7)

The focus on the supply of the next generation of scientists and thus on students in school who may go on to further study is troublesome as it does nothing to increase diversity or social justice in science education. Indeed, one of the key policies from STEM designed to increase the numbers of students, that of promoting triple science, is problematic as 'Selective practices around triple science create and perpetuate social inequalities' (Archer *et al*., 2016, p. 1), as discussed in Chapter 8.

9.5.2 Diversity

In comparing the data sets, it is noticeable that many of the teachers (Chapter 7) were concerned about equity in education. In particular, the opt-in/opt-out nature of most STEM activities in schools was considered problematic. The teachers were clear that they wanted their collaboration to benefit all pupils, not only those who might go on to further study. Indeed, the 'Get into teaching' website puts the desire for equity at the centre of its claim about teaching as a career, suggesting (one would hope accurately) that:

> Every day you'll get the chance to inspire young people […] making sure every pupil gets the same access to a quality education and the opportunity to succeed. (DfE, 2017)

In comparison, while most of the policy maker participants mentioned the need to increase the numbers of young people choosing to continue to study STEM subjects at some level, only two mentioned the need to increase the diversity of those people by increasing numbers of women and ethnic minorities studying STEM subjects (particularly physical sciences and mathematics).

A further social justice issue was raised by SF who noted that at undergraduate level the STEM subjects are dominated by those from the independent sector and suggested that action was required to counter that imbalance:

> *And clearly we do still have many elite independent schools and one of the things that is shocking [… is] the fact that such a high proportion of people doing A-level sciences and maths, and getting high grades and then studying STEM subjects at university, go through our independent schools.* [SF]

As the national STEM policies were strongly focused on those already identified as high achievers (Wong *et al.*, 2016), the lack of diversity or awareness of social justice issues in STEM policies may help to explain why the evaluation of the government STEM education initiatives found that they struggled to gain traction in schools (NFER, 2011).

9.6 Beliefs and identity

Collaborating with colleagues from another department can be challenging for teachers in a number of ways. It can challenge their identity as a subject teacher particularly when they are expected to teach out of specialism. Data from the School Workforce Census (DfE, 2011) shows that only around 5 percent of mathematics teachers regularly teach science and around 5 percent of general science and 5 percent of physics teachers also regularly teach mathematics. While there are problems with this data, not least in the definition of a science or a mathematics teacher, expecting science and mathematics teachers to teach across specialisms (aside from outside science specialism as over 80 percent of science teachers do) is apparently relatively rare. Teachers often identify with their subject (Siskin, 1994) and requiring them to teach something else can cause them to lose their passion as a result and the schools' data (Chapter 7) suggests may even result in them leaving to work elsewhere.

Carlone and Johnson (2007) argue that identity involves competence, performance and recognition. Teaching outside their specialism can lead to teachers feeling less competent, perhaps performing less well in the classroom and having that recognised by colleagues and students. It can thus challenge their identity as a 'good teacher' also leading to a loss of passion for their role.

Boaler (2002) has argued that for students to use mathematics successfully outside the classroom, they need to develop a productive relationship with the subject with such a relationship developing, at least in part, through feelings of confidence in relation to mathematics. The same will also be true for teachers. If they do not have a productive relationship with mathematics developed through confidence and positive experiences with mathematics then they will not look for ways to bring mathematics into the classroom, they are more likely to avoid doing so as much as they can. Matthews (2014) argues that Australian science graduates are not particularly good at mathematics; Cockcroft (1982) found that science graduates' confidence with mathematics was not as high as might be expected and thus lack of confidence with mathematics may be relatively common among science teachers.

There is perhaps a difference between requiring a mathematics teacher to teach science and a science teacher to teach mathematics. Western democracies prize logical-mathematical thinking (Crombie, 1994) more highly than other types of intelligence (Caprara & Cervone, 2000). When this type of thinking is so valued, it could be difficult for a science teacher to admit to a limited knowledge of mathematics. Lack of knowledge of science could be seen as a lack of knowledge of science 'facts' which could be an easier thing to admit to as it does not require logical-mathematical thinking. Mathematics teachers frequently do not have a strong science background so there would be no expectation or loss of face in admitting that they do not know scientific facts. Science teachers are expected to be highly mathematical, even if that expectation is unrealistic, and thus admitting to struggling with mathematics could also challenge teachers' identity, perhaps that of teaching an elite subject.

9.7 How much mathematics in science?

There have been a number of arguments for either increasing or decreasing the amount of mathematics within science and some discussion about what mathematics should be included. In the early 1980s some science educators including Shayer and Adey (1981) argued from a Piagetian standpoint that the cognitive demands of secondary science were too high and that the mathematics which was focused on in school curricula was often not the most appropriate.

Following the introduction of the national curriculum in 1989, in a study about key stage 3 science, Dodd and Bone were similarly concerned that the mathematics in science was not accessible to many of the students. They suggested that science teachers' perception that students had not covered all the mathematics they might need for science was largely correct, but that the fault did not lie with mathematics teaching, rather with the expectations in science teaching being too high:

> The major problem lies in the considerably more difficult mathematics which the science teachers, perhaps naively, may believe has been covered by the mathematics department during the KS3 schemes of work. The inevitable conclusion is that some topics in the KS3 National Curriculum for science implicitly assume a level of mathematics capability which is significantly beyond the majority of pupils. Little wonder that the confidence of pupils in using their mathematics in science is so poor. Some of the mathematics required for KS3 science, particularly algebra and the transpositions of formulae, is not included in the KS3 National Curriculum for mathematics. We suggest that the solution is clear: such topics should be removed from the KS3 science programmes of study. (Dodd & Bone, 1995, p. 105)

Here we see evidence of effects in schools of very limited collaboration between the writers of the science and mathematics curriculum: the science curriculum implicitly assuming mathematics which is beyond most pupils, which has an impact in schools and with pupils. In Chapter 8 I demonstrated that the original mathematics and science groups writing the curricula were kept apart, and that the government had no interest in fostering collaboration between the writing groups. I also demonstrated that in the writing of the latest national curriculum there was once again very limited, or no, collaboration between the writers of the mathematics and the science curricula. Thus it would not be surprising to see the types of problems described by Dodd and Bone begin to surface again in schools as the new curriculum is introduced, particularly as the latest key stage 4 science curriculum contains a lot more mathematics than previously. Such issues will not be present in the data from this study as it was conducted prior to the introduction of the new, more mathematical, curriculum, but further work is needed to explore the experience of students and their science teachers with the mathematical content of the new curriculum.

I have shown that the impetus for more mathematics in the latest curriculum stems, at least in part, from three key beliefs. Firstly that more mathematics will make science more rigorous. Secondly, as discussed above (Section 9.3.1), that it will improve students' overall mathematical confidence and achievement. And thirdly, putting more mathematics in science stems from the desire to increase the authenticity of science which, as I have demonstrated (Section 9.5.1), is an ideology which prioritises the needs of those who are likely to continue to study science.

I broadly agree with Osborne, who argues that:

> Avoiding the opportunity to use mathematical forms and representations is a failure to build students' competency to make meaning in science. Hence opportunities to engage in the practice of mathematical and computational thinking are an essential experience in the teaching and learning of science. (Osborne, 2014, p. 188)

However, for the use of mathematics to genuinely involve the engagement of students with the practice of mathematical and computational thinking there is a need for time within the curriculum. The inclusion of 14 different three-part equations (most of which must be memorised) within the physics curriculum, plus more in chemistry and biology, plus other types of equations, will almost certainly reduce time spent thinking about the mathematical implications of each. As I demonstrated earlier (Section 9.4.1), the context is important as just because students can understand and think proportionally in one context does not mean that they can automatically do so in another. I argue that science could better support students' mathematical thinking and mathematical development if there were less mathematics within the curriculum but what was present was used to promote mathematical thinking.

It is not enough just to assume that students will have learnt what they need in mathematics and be able to use it seamlessly in science, for at least two reasons. Firstly that transfer is challenging for the majority of students, as virtually all authors who have seriously studied it agree, and most students will need time and support to use mathematics effectively within science. Secondly, that the type of mathematical thinking required in science is markedly different from that in school mathematics itself, as in science the results of calculations or graphs need to be applied back to the real world or phenomena in question. This is a different skill to that required in mathematics.

Much of academic science is indeed quantitative, but there is undoubtedly a place for a qualitative understanding to precede or, in some cases at school level, replace a formal mathematical approach. The assumption that if the science does not involve numbers it is not proper science and is not worth students' time is not correct. Osborne (2011, 2014) identifies six practices of science which are not necessarily quantitative and are equally worthwhile: asking questions and defining problems; developing and using models; planning and carrying out investigations; constructing explanations; engaging in argument from evidence; and obtaining, evaluating and communicating information. If including too much and too high level mathematics results in students losing confidence, as Dodd and Bone (1995) suggest, then it will not have the effect of increasing rigour or improving students' mathematical confidence, two of the reasons given for increasing the amount of mathematics within the curriculum.

As with any aspect of curriculum policy, there will probably never be agreement reached about how much mathematics should be in science qualifications at any level. But qualifications which must be sat by all students must be accessible to and worthwhile for all, including the majority who will not continue to study science beyond the age of 16.

9.8 Conclusion

I have thus thoroughly discussed the answers to the research questions, namely:

1. How and to what extent can mathematics and science educators work together?
2. What are the barriers to effective, mutually beneficial, collaborations between mathematics and science teachers?
3. How might these barriers be addressed?

I have shown that collaboration, particularly mutually beneficial collaboration, between mathematics and science teachers is far from straightforward. Bringing theory to bear in analysing the data has allowed a far more nuanced and detailed picture to emerge than focusing on the practicalities alone. In the next chapter, I reflect on the study as a whole before considering the implications of the findings for policy makers, for practice in school and for science education research.

Chapter 10
Reflections and Implications

I set out in this study to ask:

1. How and to what extent can mathematics and science educators work together?
2. What are the barriers to effective, mutually beneficial, collaborations between mathematics and science teachers?
3. How might these barriers be addressed?

In Chapter 9, I thoroughly discussed the answers to these questions. In this chapter I reflect on the methods and methodology of the study and consider the implications of my key findings.

10.1 Reflections: methods and methodology

My aim was to explore the relationship between school science and mathematics education from multiple perspectives to gain as full a picture as possible of the issues and barriers surrounding collaboration. I did this initially by interviewing both teachers and policy makers. Walford suggests that it is easier to gain access to participants of this type when one exploits 'pre-existing links with those in power' (2012, p. 112). Nine of the 21 policy maker participants were previously known to me and it is undoubtedly the case that at least some of them agreed to be interviewed because of that existing relationship. Further doors were opened to some of the other participants as I was known by reputation from my years working in science education including for the Royal Society of Chemistry, the Royal Society, Gatsby Science Enhancement Programme, and the Nuffield Foundation. The extent to which pre-existing links were important was demonstrated in how much harder it was to find mathematicians willing to participate. With fewer existing contacts I had a far lower acceptance rate than I did with science education policy makers.

The reputational snowball proved a powerful means of both identifying and making contact with potential participants. A few key interviewees introduced me to others with whom I would have had no way of making contact through any other means: I am extremely grateful to them as this study would be much the poorer without their support. To be introduced by someone who is respected meant I was granted a level of trust which may not otherwise have been possible. To make a big snowball, however, requires at least some snow to begin with and I do not think this method would have worked had I (or my supervisors) not had the existing contacts within the field of STEM education.

In interviewing policy makers, the key limitation as discussed in Chapter 5 (Section 5.2.1.1) is that there were fewer mathematics educators who took part due to a lower acceptance rate among mathematicians. I stopped interviewing in part as data saturation was being reached, but also as with the higher acceptance rates from science educators I would have needed to secure interviews with several mathematicians if the data was not going to be completely skewed by science educators. Furthermore, many of the policy makers who declined did so due to a disinterest in the topic. For science educators the lack of interest was usually in STEM and STEM policy, some expressing that a dislike for STEM meant they would not take part. For the mathematics educators it was a dislike of STEM or a lack of interest in collaboration or in the overlap between mathematics and science. Thus the data collected represent mathematicians, in particular, who have more interest in collaborating with science. It is largely fruitless to speculate what might have been said by people who I did not interview, but nonetheless the policy makers data set is probably skewed towards the views of those with positive conceptions of STEM and mathematics-science collaboration.

I interviewed teachers in schools where science and mathematics departments worked together. I interviewed both mathematics and science teachers as well as two technology teachers, to gain as broad a perspective as possible into the nature of their collaboration. As the reputational snowball was proving so useful in interviewing the policy makers, I also tried it with schools. However, only one participant could suggest other schools where similar collaborations were taking place, suggesting both that collaboration which does arise is a local, individual, response to a stimulus and that schools which collaborate are not networking with one another. The one recommendation I did receive did not result in the school taking part.

As with the policy makers, existing contacts and reputation were once again critical to gaining access. Attending professional development at STEM NRICH and the ASE conference allowed me to make face-to-face contact with teachers and led to access to three of the schools. In the other three I had an existing relationship with someone in the school, even though in one case they were not one of the participants. Meeting me, or knowing someone who knew me, was thus critical in establishing sufficient trust for me to be invited to visit the school. None of the schools I contacted without an existing relationship replied to any email or letter sent. In each school I visited I was asked about my own teaching experience, and having several years of experience teaching in both the state and independent sector was again critical in gaining teachers' trust.

Thus in visiting schools I was limited to people with whom I had an existing relationship, even if that relationship was very brief in some cases. There may well be schools with interesting collaborations where I was unable to gain access. This was not, however, intended to be an in-depth study of every school where collaboration takes place. In spite of the limitations, I identified a range of types of collaboration in the schools and also ensured that the schools recruited represented a broad geographical area. While I would have welcomed the opportunity to visit further schools, the six which took part all provide unique insights into the challenges and benefits of collaboration.

10.1.1 Data analysis

Initial analysis of the data allowed me to identify a number of mainly practical barriers and affordances for collaboration, but it was bringing theory to bear on the data which allowed a more detailed and nuanced picture of the relationship between school science and mathematics to emerge. Asking, as Bernstein (2000) suggests, who is responsible for initiating the collaboration and whether they are dominating or dominated, in other words whether they originated from the top or the bottom of the institution, helped to illuminate that it was senior managers, and particularly the headteacher, who was responsible for both promoting and reducing the amount of collaboration. It was not, as I had imagined, primarily the heads of science and mathematics.

Bernstein (2000) similarly contends that when the boundaries between subjects and departments are weakened one should ask who benefits. Asking this question allowed me to identify the asymmetric *dependency* and consequently the asymmetric *benefits* of collaboration for science and mathematics departments. The asymmetric nature of the relationship between school science and mathematics is not discussed in the literature, but is critical when thinking about whether and how collaboration can be mutually beneficial.

The writing of Stephen Ball has been useful in trying to understand the policy landscape and how schools react to policy. For example, the idea of policy networks (Ball & Junemann, 2012) was particularly helpful when considering the reputational snowball and how to find participants. The importance of unpacking the relationship between schools and policy (Maguire, Ball, & Braun, 2012) when considering how schools respond to policies including the national curriculum and the government's STEM initiatives. The importance of considering the micropolitics, relationships and decision making which take place inside schools (Ball, 1987). The role of Ofsted in determining school policy, and how schools react and respond both before and after inspections (Perryman, Maguire, Braun, & Ball, 2017). His study of the introduction of the Education Reform Act (Ball, 1990) helped in understanding the political atmosphere surrounding the substantial changes to education policy in the late 1980s.

Fensham (2009) argues that in researching any given policy we should ask whose values are favoured, which stakeholders have been successful in its shaping and which groups in society are advantaged and disadvantaged by the resulting education practices. Asking such questions has highlighted the importance of two key players in the national STEM policies: Lord David Sainsbury and Professor Sir John Holman. It has also highlighted the way in which the perceived needs of high status students, those who might be expected to continue to study STEM subjects post-16 and at undergraduate level, are prioritised in science education policy, including in the development of curricula which will be studied by all students.

Considering the transfer literature, while it is diverse and disparate, it demonstrates that the vaccination view of mathematics education (highlighted by Osborne, 2014) would appear to be somewhat naïve. The findings of Redish and Kuo (2015) suggest that there is a separate maths-in-physics dialect or language which students need to be taught how to use, or be enculturated into. I (Wong, 2017) have similarly demonstrated that the way graphs are used in mathematics and science is different. As a result, the content and skills students need to be taught in science with respect to the construction and interpretation of graphs is substantively different to those required in mathematics.

Using the lenses of teacher beliefs (Wallace, 2014; Glackin, 2016) and identity (Boaler, 2002; Carlone & Johnson, 2007) highlights that collaboration can challenge teachers' views of themselves as both 'good teachers' and as 'subject teachers.' Such a challenge can considerably reduce their job satisfaction and can potentially lead to them choosing to leave. When there is already a shortage of STEM teachers, it is understandable if senior leaders are reluctant to introduce changes to working practices which could lead to the loss of valued staff. The lens of teacher beliefs also highlighted the need for teachers to believe in a change in practice, such as collaborating, in order to implement it effectively.

Overall, then, it is possible to see how collecting a range of data, and analysing that data through a range of lenses, has allowed a more in-depth and nuanced picture of the relationship between science and mathematics education to emerge.

10.2 Implications

In the light of the findings from this study, there is an opportunity to ask what the implications are for policy, for practice, for theory and for future research. I consider each in turn.

10.2.1 Implications for policy

I have demonstrated (Chapter 8) that the National Curricula for mathematics and science have been developed almost entirely separately from each other, at least in the most recent and the original versions. I have shown that teachers in schools are aware of, and frustrated by, the separation between the two curricula (Chapter 7). When the science curriculum is developed separately from the mathematics curriculum, and particularly when there is significant mathematical content in the science curriculum, there is a risk that that mathematical content is too demanding (as discussed in Chapter 9, Section 9.7). The implication for policy development is not, as some science educators sometimes seem to think, that mathematics needs to change to suit the needs of science. It is important that science educators recognise that mathematics has links to many areas of the curriculum, not just to science. Instead, I argue that in future curriculum development the writers of the mathematics curriculum should act as advisors to the developers of the science curriculum, to ensure that the mathematical demands are appropriate. To do so would clearly take time, and the time for such consultation should be built into contracts for curriculum development by the government. Where the mathematics required in science is not present in the mathematics curriculum then it should be highlighted as such in the science curriculum, and time allowed for its coverage.

I have shown that there are differences in the way language is used in mathematics and in mathematics-in-science, and have discussed (Chapter 9, Section 9.4.2) some of the reasons for these differences. There are differences between mathematics as used in mathematics itself and mathematics as used in science. It is important to highlight the differences between mathematics and science, as well as the similarities, to help teachers to make these differences clear to students. Expecting either subject to change their use of language is probably not reasonable, as I have shown that there are good reasons for many of the differences, including differences in epistemology. Nevertheless, where possible, language should be harmonised and where it is not possible, the differences should be clarified. The ASE publication *The Language of Mathematics in Science* (Boohan, 2016) is a good place to start.

When mathematics is put into the science curriculum it is important to recognise that it will need to be taught within science and not to assume a simple model of transfer. Working with mathematicians on the mathematical aspects of the science curriculum, or being clear about the differences in language between the two curricula, will likewise not improve transfer. Time needs to be allowed within the science curriculum for teaching the mathematical aspects of science. While there will probably never be agreement about what is the 'right' amount of mathematics within science, the current curriculum is probably too heavily biased towards quantitative science.

There may be advantages to a discussion within the science community about what mathematics should be included for each separate science, recognising that the individual science disciplines vary in how they use mathematics, as in many other ways (Jenkins, 2007). There may be advantages to a focus on what is deemed important rather than trying to include every possible aspect of mathematics, to allow teachers time to teach mathematical thinking in science rather than needing to rely on the use of 'tricks', as discussed in Chapters 7-9.

Concerns for social justice should be at the fore of policy making, and science for all the focus of any curriculum followed by all students (see Chapters 8 and 9). Science curricula should not be aimed primarily at those who may or will continue to study science particularly post-16 but also post-18, as doing so is ethically dubious (Hodson, 1993). It is, in any case, a spurious argument that curricula should meet the needs of those who will continue to study the subject; any curriculum should be designed to build on the one which went before.

Universities should similarly take accurate account of what their incoming undergraduates can actually do, rather than expect changes to school curricula to meet their perceived needs. There are examples of university departments which have successfully taught their students the mathematics required for their degree (see, for example, Grove & Pugh, 2015) and it would be better to focus on sharing good practice within the university sector than to change the school curriculum for all to suit the needs of the few. Part of the universities' concern is the small amount of mathematics which many students have studied from the age of 16-18 as a result of the low proportion of students who continue to study mathematics in post-compulsory education (Hodgen, Pepper, & Ruddock, 2010). The Royal Society *Vision Project* suggests a broadening of the curriculum for 16-18 year olds such that they study five or six subjects rather than three, including mathematics for all students (The Royal Society, 2014). Such a change may be a better way of improving students' mathematical confidence and competence than introducing a large proportion of mathematics into science qualifications.

10.2.2 Implications for schools' practice

Science and mathematics departments often operate largely independently of one another. This situation is reinforced by the National Curriculum, assessments and Ofsted inspections being also largely independent of each other (Chapter 7). Furthermore, departments are often in competition with each other for resources including money, physical space and high achieving students. Such competition can lead to an often uneasy, or even hostile, relationship between heads of departments (Ball, 1987). From the collaborating schools which participated in this study, it would appear that there are two main ways in which such issues can be overcome. The first is through senior leadership team involvement, with leadership teams or headteachers encouraging or compelling collaboration. One way of facilitating collaboration is through the creation of science and mathematics faculties, as seen in three of the schools in this study. Such faculties are not guarantees of collaboration, however, in the absence of continued support. Furthermore, it is important to consider what might be lost as a result of creating larger teams. In many state secondary schools each department can have in excess of 12 teachers, thus the faculty will contain at least 24 teachers. Such a large group could lead to the loss of a feeling of nurture and support that often exists within a department. Bernstein (2000) argues that it is not possible to have both a strong department culture and strong relationships across the school. It is not clear that it would be in the best interest of teachers or students that departmental relationships be broken down in favour of cross-department ones.

The second way to address the issues is through informal conversation in a pre-existing relationship (Chapter 7). To have discussions which reveal one as lacking knowledge it is necessary to trust the person with whom one is conversing. As such, forcing these types of conversations is unlikely to be successful and knowing the person a necessary prerequisite to fruitful conversation. I have shown in this study that conversations to better understand the mathematics curriculum were a good investment of time for science teachers and produced valued professional learning (Chapter 7). It is, however, important to be clear what can, and what is unlikely to, result from such conversations. A better understanding of the mathematics curriculum will not, in itself, ensure that students can use mathematics more effectively within science. Conversations are unlikely to result in the mathematics department changing the way it teaches to support science colleagues. Conversations can, however, help science teachers to understand students' difficulties in using mathematics, and help them in planning to take effective account of those difficulties. Taking effective account of what students already know is not a new idea in science education, as demonstrated by the large number of studies about misconceptions, but it is just as important to take account of what students understand and can do mathematically in science.

I have identified the existence of 'maths blame' (Chapter 9) whereby science teachers have a tendency to blame mathematics colleagues for students' difficulties in using mathematics in science. Maths blame arises directly from the dependency of science on mathematics and the unrealistic expectation science teachers can have of students being able to 'transfer' mathematics they may not even have covered into science without additional support. Invoking maths blame demonstrates science teachers not being willing to take responsibility themselves for teaching the mathematics required within science. I have shown that maths blame can arise even when students have not covered the mathematics which science teachers were anticipating. Collaboration in and of itself is unlikely to 'improve transfer', or to improve students' use of mathematics in science. It can, however, help science teachers to have more realistic expectations of students' use of mathematics.

10.2.3 Implications for methodology

It would, conceivably, be easy to blame the general lack of mathematics-science collaboration in schools on teachers: perhaps they choose not to collaborate or are not interested in so doing. However, unravelling the situation in the policy sphere helps in understanding the context in which schools, and therefore teachers, operate. While teachers' identity and beliefs did apparently make a difference in their decisions regarding collaboration, the policy context was equally, if not more, powerful in explaining their actions. This study was unusual in mapping both practice and policy and can demonstrate the impact that policy has on the practice of mathematics-science departmental collaboration. Future studies of teacher practice would undoubtedly benefit from similar attention to the policy sphere.

10.2.4 Implications for theory and future research

10.2.4.1 Asymmetric dependency and maths blame

I have demonstrated the asymmetric dependency which exists between school mathematics and science, leading to asymmetric benefits from collaborating (Chapter 9). Asymmetric dependency will be a useful theoretical tool to allow future researchers to identify benefit in collaboration and when theorising about potential benefits to mathematics and science departments of any joint intervention. It is unlikely to be helpful to recommend that departments work together more closely when the majority of the work is expected to come from the mathematics department and the majority of the benefits accrue to the science department. Such asymmetries are highly unlikely to lead to sustained collaboration.

As a result of asymmetric dependency, the idea of working in a way which is mutually beneficial is likely to be unrealistic. There is an asymmetric need for knowledge and understanding: science teachers need to know and be able to use mathematics and it is helpful if they understand the order and content of the mathematics curriculum. There is far less need for mathematics teachers to know any science or to understand the order and content of science curriculum. When calling for closer alliances between departments the likely greater benefit for science should be acknowledged and consideration given to ways in which there can also be potential gains for mathematics departments.

In this thesis, I have identified and articulated the concept of maths blame (Chapter 9). Blame of others could be conceptualised further, particularly in instances where teachers try to avoid taking responsibility for what students can do in their teaching, instead blaming students' failures and difficulties on another group. It would be possible to identify, perhaps, 'primary blame' among secondary teachers. Are university tutors' unrealistic expectations of undergraduates' mathematical abilities (as identified, for example, by Koenig, 2011) evidence of 'school blame'? What impact might the voicing of such 'school blame' have on school curricula, particularly in an era where the government has encouraged the involvement of universities in the writing of those curricula? Koenig herself recommends that 'there needs to be a more significant mathematical component in A-level biology and chemistry' (2011, p. 1) to address the difficulties experienced by undergraduates in the biosciences. Should curricula for the many really be written with the needs of the few in mind?

It is interesting that there does not seem to be a similar ‘English blame’. For example, when six-mark questions returned to GCSE science (following the SCORE report in 2009), science teachers looked for ways to teach students to write in science, not, as far as I am aware, by blaming English teachers for students’ difficulties. Do science departments really blame mathematics departments for students’ difficulties with mathematics, but not view English departments as being responsible for students’ communication difficulties? And if there is a difference, why is this the case? There do not seem to be calls to work with the English department to improve students’ writing in science as there are calls to work with the mathematics department to improve students’ use of mathematics in science, and it is not clear if or why there is a difference.

10.2.4.2 Transfer

Redish and Kuo (2015) identified differences between mathematics and physics in the way in which mathematics and mathematical language are used. They suggested that such differences help to explain why ‘transfer’ is difficult between mathematics and physics, because the tasks are actually not the same. Physicists, they argue, use mathematics in describing physical systems and use their knowledge of those systems to constrain the mathematics, thus keeping the mathematics simpler than would otherwise be required (Chapter 9). Learning to be a physicist involves learning to use mathematics as a physicist, or to speak a different dialect of mathematics. Their ideas could have profound consequences for how transfer between mathematics and science is viewed and could help to explain why it is so difficult. If their findings similarly apply to school science, and evidence from Wong (2017) suggests that they might in the case of graph work, then it would help to explain why transfer between the two subjects can be so difficult for students, but would also limit how useful mathematics in science can be to mathematics itself. Improving students’ broader understanding of mathematical processes is one of the reasons given for increasing mathematics within science (by, for example, Fairbrother, 2008).

Isomorphic problem solving questions are often used when exploring transfer between mathematics and science (for example by Bassok & Holyoak, 1989; Scott, 2012; Zhang, Orrill, & Campbell, 2015) but there are significant difficulties in ensuring that problems genuinely are isomorphic. If even educational researchers find it hard to write genuinely isomorphic problems, then the question arises as to how often problems in school science are genuinely isomorphic to students' learning in mathematics and *vice versa*. If problems are in fact different, and if the rules (or applicability conditions) are different in different contexts, it helps to explain the observations of many authors that students need help to transfer their learning and supports Schwartz, Bransford and Sears' (2005) argument that prior knowledge would be better considered as 'preparation for future learning' than a parcel of knowledge and skills which can be opened in different contexts and used without further support.

Some authors such as Pang and Good (2000) and Zhang *et al.* (2015) suggest that it should be relatively easy for teachers to find points of overlap in the content of mathematics and science. However, I found that making connections across the subjects was not straightforward for teachers working in schools. While it might be tempting to assume that the problem is with these teachers, all the teachers in this study were highly regarded within their schools and, moreover, working across departmental boundaries. A deficit model of the teachers is therefore not appropriate and the problem is not with the teachers, but rather with the presupposition. Having the knowledge and appreciating the connections across just one subject is recognised as being demanding and evidence of expert practice (Turner & Rowland, 2011); seeing connections across two disciplines when the teacher probably teaches in only one is clearly not as simple as many authors apparently assume. Difficulty in seeing connections between the subjects is thus a significant barrier acting against collaboration which should not be ignored.

10.3 Further work

As the relationship between school science and mathematics education is under-explored it is not hard to suggest where more work is needed.

We need a research agenda that addresses the interaction between learning in mathematics and in science, and explores how students bring mathematics to bear on a problem in science. Such an agenda may help to finally lay to rest the notion of vaccination, or simple transfer from mathematics to science, and with it maths blame. It may also help to answer the question of whether and how mathematics in science can contribute to students' wider mathematical development.

There is also a need for further exploration of the way mathematics is used in science compared to how it is used in mathematics. Are the differences found by Redish and Kuo

(2015) between university mathematics and physics also evident in school science? And are there differences between the individual science disciplines in how mathematics is used? If so, are teachers aware of those differences and how do they take account of them in the classroom? These questions could be approached through classroom observations and through a study of text books and teaching resources.

Confirmation that students do transfer their learning, at least sometimes, perhaps comes most strongly from the evidence of negative transfer reported by teachers in this study. Negative transfer is where prior learning hinders or acts negatively on students' performance in another subject. Teachers pointed to a number of cases of negative transfer, often related to language differences between the subjects. Consequently it would seem that teachers most often notice transfer taking place when it is problematic, but this negative transfer does show that transfer can and does occur. The existence of negative transfer does not mean, though, that students will be able to use mathematics in science as teachers would wish. Indeed, Whitty, Rowe and Aggleton (1994), in a study on oral work across the curriculum, found that if students understood the distinctive differences in how subjects use oral work then they were inhibited from using their knowledge across different subject discourses. Schwartz *et al*. (2005) argue that while negative transfer may be seen initially, prior learning can be supportive of future learning. Further work is required to explore whether students' appreciation of how mathematics is used differently in different subjects similarly inhibits them in transferring their learning, particularly as it may help to explain observations by Porkess (2013) and others that students who achieve highly in mathematics can struggle to use mathematics in science. It is also required to explore whether and how mathematics can indeed be preparation for future learning in science, as Schwartz *et al.* (2005) argue, and how science teachers can best support students in their use of mathematics.

Behind some of the calls for an increase in mathematics in science is the belief that including mathematics in science has a positive impact on mathematics, although there is no evidence to demonstrate such transferability between subjects and designing a study to demonstrate transfer would be extremely challenging. One of the few projects to demonstrate cross-department transferability is CASE (Adey & Shayer, 1993) where work in science led to higher results in English as well as science at the end of compulsory schooling.

In this study I focused on teachers and on policy makers. There is a need to find out how students use and view mathematics in science as there is a dearth of research in this area. Much of what does exist relies on isomorphic problem solving which, as we have seen, is problematic. Instead, students' use of mathematics in science could be explored: through lesson observations of the introduction of quantitative topics in science; by asking students, individually or in focus groups, to solve quantitative science problems using think aloud protocols; and by looking at how a broad range of students tackle quantitative problems in science, not just those students likely to go on to further study.

In this study I researched six schools through one-off visits. It may be fruitful to carry out a longer and more in-depth ethnographic study of departments beginning to collaborate, to include department meetings, lesson observations and spending time in the department, as well as interviews with the teachers involved.

Further work is needed to investigate the experience of students and their science teachers with the mathematical content of the new curriculum. Such an exploration may help to answer the question of how much, and which, mathematics can be included most profitably in the science curriculum.

Further work might also be carried out into how science teachers can use mathematical ideas to encourage mathematical thinking in science, rather than relying on 'tricks' like the 'triangle' (as discussed in Section 9.3.1). Perhaps the triangle could be considered a pictorial representation of a proportional reasoning problem which helps students understand or a useful scaffolding device to support students in manipulating proportional relationships, and thus should not be dismissed as simply a trick. Exactly which it is should perhaps be the focus of further research and may well be different depending on how it is used by individual teachers.

10.4 Final thoughts

In this thesis, I have explored the many reasons underpinning calls for greater collaboration between mathematics and science, and have identified two main objectives. The first is to improve transfer between the disciplines. However, in examining the likelihood of transfer I have identified two key problems. Firstly, given the asymmetry of dependency, and thus benefit, in the relationship between mathematics and science, science is always likely to be the greater beneficiary. Secondly, there are significant differences in the way in which mathematics is used in mathematics itself and in science such that the notion of simple transfer or a mathematics ‘vaccination’ is naïve, even where there is collaboration. Furthermore, such collaboration is made challenging even by variation in teaching strategies for different mathematics classes within a single school; attempts at harmonisation reduce teachers’ agency and their freedom as professionals to differentiate as they deem appropriate.

The second argument for collaboration builds on the notion that there is substantial overlap in content and thus greater collaboration would be useful, not least in saving time in covering the curriculum. This argument is related to that of transfer as it assumes that content covered in one discipline will be able to be used in the other, and thus the problems identified with transfer similarly apply. Furthermore, my analyses highlight the difference in discourse which led to experienced teachers struggling to find meaningful points of overlap between their curricula.

There are significant boundaries between mathematics and science in schools, strengthened by government education policy and its enactment. While boundary crossing is possible, it is challenging and, as Newman (2003) suggested, does not necessarily bring about the expected benefits. Bernstein (2000) has argued that when there is strong classification, and thus insulation between departments, it is hard for staff to relate to each other in terms of pedagogic discourse, as each is differently specialised. My findings agree, teachers in departments did find it challenging to collaborate and to find meaningful points of overlap in their curricula. Furthermore, I would add to Bernstein and argue that it is naïve to simply suggest that working together will necessarily solve identified problems, particularly the problem of students’ use of mathematics within science. Such a view is narrow and ignores the boundaries created by government policy, the difference in how mathematics is used across the subjects and just how challenging boundary crossing is. Rather, my findings here point to the importance of working with greater collegiality, providing more information about exactly what mathematics is covered and when in both mathematics and in science, at school level, but perhaps particularly in the development of curriculum policy. There will always be an asymmetry of dependency, science will always be more dependent on mathematics than *vice versa*, but through greater collegiality and understanding we could reduce the expression of maths blame and hopefully ensure a more beneficial situation for both learners and teachers.

Glossary

academy	A state school which is not in local authority control. It may answer directly to the government or be part of a multi-academy trust.
ACME	The Advisory Committee on Mathematics Education. It was set up in 2002 by the JMC and the Royal Society, with the secretariat housed at the Royal Society in London. It aims to develop advice to influence mathematics education policy. It is funded by the Department for Education, the Wellcome Trust, the London Mathematical Society (LMS) and the Institute of Mathematics & its Applications (IMA). From 2002 to 2015 it received funding from the Gatsby Foundation.
A-level	General Certificate of Education Advanced Level. A qualification taken by around 50% of 16-18 year olds in the UK. Students usually choose 3 subjects; there are no compulsory subjects.
AQA	The largest of the awarding organisations, it is an independent education charity.
ASE	The Association for Science Education. Formed in 1963 by the merger of the Science Masters Association and the Association of Women Science Teachers. The only UK professional body for science educators.
attainment targets	These set out what a pupil is expected to achieve in every subject at each key stage in the National Curriculum
awarding organisation	Previously known as exam boards and then awarding bodies. There are 3 in England (AQA, OCR, Edexcel) which are in competition with each other. They write specifications and examinations, and award qualifications.
Certificate of Achievement	A qualification for students who would struggle to achieve the lowest grades at GCSE. Now known as Entry Level qualifications.
CSE	Certificate of Secondary Education. A lower level and status qualification taken by the majority of 14-16s. Last awarded 1987.
Department for Business, Innovation and Skills (BIS)	Sometimes the Department for Trade and Industry (DTI), and also briefly known as the Department for Innovation, Universities and Skills. It worked with the Department for Education, particularly on aspects of STEM policy.
Department for Education (DfE)	This name is generally used throughout for clarity but it has had a variety of other names in the last 25 years including the

	Department for Education and Science (DfES), the Department for Education and Employment (DfEE), the Department for Children, Schools and Families (DfCSF), and the Department for Education and Skills (DfES).
Edexcel	An awarding organisation, part of international education business Pearson.
Gatsby	Lord David Sainsbury's charitable foundation
GSCE	General Certificate of Secondary Education. A qualification taken by the vast majority of 14-16 year olds in England since 1988.
High Level STEM strategy group	A formal network which aimed to join up STEM across all phases of education including DfES, the DTI, other government departments and external stakeholders, and to make recommendations to Ministers about national STEM priorities.
Higher Education Academy	A company and charity which aims to improve the status and quality of teaching in higher education. The members are Universities UK and the Guild of Higher Education.
JMC	The Joint Mathematical Council of the United Kingdom, the umbrella organisation for mathematics. Formed in 1963, there are 21 separate societies which are part of the JMC, including the Royal Academy of Engineers and three separate mathematics teaching organisations.
Key stages	The national curriculum is organised into blocks of years called 'key stages' (KS). Primary school covers key stages 1 and 2. Key stage 3 is for age 11-14 and key stage 4 for 14-16, although some schools consider key stage 3 to be two years long and key stage 4 three years. There were originally national tests in English, mathematics and science at the end of each key stage, but the key stage 3 tests have been abolished, as have the key stage 1 and 2 tests for science.
OCR	Oxford, Cambridge and RSA. An awarding organisation.
Ofqual	The Office of Qualifications and Examinations Regulation, it regulates qualifications, examinations and assessments in England. It is a non-ministerial government department that was created by an Act of Parliament in 2010, so consequently it would take an Act of Parliament to remove it.
O-level	A UK qualification taken by 25% of students aged 14-16. Last awarded 1987.

Programme of Study	The National Curriculum is organised into Programmes of Study in each subject. They set out what content needs to be covered in each subject at each key stage.
QCA/QCDA	The Qualifications and Curriculum Authority (QCA), later the Qualifications and Curriculum Development Agency (QCDA). This was disbanded when there was a change of government in 2010, with responsibility for writing and maintaining the curriculum moved into the Department for Education.
SCORE	Science Community Representing Education. From 2006-2015 the Institute of Physics, the Society of Biology, the Royal Society of Chemistry, the Association for Science Education and the Royal Society worked together as SCORE to develop science education policy. The Science Council was a founding partner. SCORE was funded by the partner organisations, Gatsby and the DfE with, like ACME, the secretariat housed at the Royal Society.
STEM	Usually refers to Science, Technology, Engineering and Mathematics, although to some it is Science, Technology, Engineering and Medicine.
subject criteria	Set out the subject knowledge, understanding and skills which must be included in a qualification, together with details about how the subject must be assessed.
subject specification	Each awarding organisation produces their own specifications for qualifications based on the subject criteria. The majority, such as GCSEs and A-levels, must be approved by Ofqual.
TGAT	Task Group on Assessment and Testing, responsible for developing the assessment of the original National Curriculum.

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Appendices

List of appendices

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12. The Space Project from Deecom
13. The Eyston mathematics and science policy

Appendix 1: Iterations of the Secondary National Curriculum

Year	Mathematics	Science
1989	The first National Curriculum KS1-4 (Department for Education and Science and the Welsh Office, 1989b)	The first National Curriculum KS1-4 17 Attainment targets, with statements of attainment for each of 10 levels (DfES and the Welsh Office, 1989)
1991	Mathematics in the National Curriculum Not much change to the content, but assessment made more manageable (Department for Education and Science and the Welsh Office, 1991b)	Science in the National Curriculum A reduction to 4 Attainment targets – roughly the 3 main sciences and investigations (Department for Education and Science and the Welsh Office, 1991)
1995		Science in the National Curriculum 10 levels become 8, plus exceptional performance Investigations changed to give more prominence to quantitative work (Department for Education and the Welsh Office, 1995)
1999	Mathematics: the National Curriculum for England Mathematics content hardly changed KS4 divided into foundation and higher First consideration of how mathematics could contribute to maths across the curriculum. (Department for Education and Employment and Qualifications and Curriculum Authority, 1999a)	Science: the National Curriculum for England Importance of science statement introduced Investigations changed to scientific enquiry Ideas and Evidence included (Department for Education and Employment and Qualifications and Curriculum Authority, 1999b)
2004		Science: the National Curriculum for England Only key stage 4 actually changed, the content of KS1-3 remained the same Links shown from science to mathematics (*not vice versa*), English and ICT Much less prescription to allow for greater breadth of offer (fits onto one page), focus on How Science Works. Set up for the 2008 changes to GCSEs.

		(Department for Education and Skills and Qualifications and Curriculum Authority, 2004)
2007	Mathematics at key stage 3. Very few changes made to the previous version. (Qualifications and Curriculum Authority, 2007b)	Science at key stage 3 changed to make it more consistent with the 2004 key stage 4 version (Qualifications and Curriculum Authority, 2007a)
2013	Mathematics at Key Stage 3 (Department for Education, 2013e) Mathematics at Key Stage 4 (Department for Education, 2013d)	Science at Key Stage 3 (Department for Education, 2013f)
2015		Science at Key Stage 4 Includes far more mathematics Far more content specified (Department for Education, 2015)

Appendix 2: Sample approach letters to schools and to policy makers, information sheets and consent forms

The Headteacher

Dear

I am undertaking some research into collaboration between mathematics and science departments in English schools. I have read/heard about with interest about the innovative curriculum which is in operation in [school name] with the [detail of collaboration]. I would like very much to come and see what happens in your school, how you make the collaboration work and what the benefits are to your staff and students.

If you agree it would entail me visiting the school, interviewing you or another senior teacher, the head of science and the head of mathematics, the equivalent posts in your school or the teachers most closely involved in the collaboration, at a time convenient to you. Each interview would take approximately 30-60 minutes. The enclosed information sheet contains some more details and do feel free to contact me with any questions you might have. I am most easily contacted by email on Victoria.wong@kcl.ac.uk or by phone on 0000000. The work is supervised by Professor Justin Dillon.

I look forward to hearing from you.

Yours sincerely,

Vicky Wong
PhD Student
King's College London

Dear [Name]

I am a first year PhD student at King's College London, supervised by Prof Justin Dillon, undertaking research into the STEM agenda and the relationship between science and mathematics education. I am interested in the history of the relationship between the two subjects in the national curriculum and how that has (or hasn't) changed with the advent of the STEM agenda. To this end, I am interviewing people who have been key in this area of policy.

Your name has been suggested by some of my other interviewees, including [...], and I wondered if you would be willing to talk to me for about 30 to 60 minutes.

There is more information in the attached document but please do feel free to ask if you would like any further details.

If you would be willing to be interviewed then we could arrange a time and a place which would be convenient for you.

With best wishes,

Vicky Wong
PhD Student

INFORMATION SHEET FOR PARTICIPANTS

REC Reference Number: **REP(EM)/12/13-26**

YOU WILL BE GIVEN A COPY OF THIS INFORMATION SHEET

Science and mathematics education in English Schools

We would like to invite you to participate in this postgraduate research project. You should only participate if you want to; choosing not to take part will not disadvantage you in any way. Before you decide whether you want to take part, it is important for you to understand why the research is being done and what your participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information.

- The aims of this research are to look at the relationship between mathematics and science in English secondary schools. In this strand of the research we will be looking at the policy making which has influenced the extent to which mathematics and science departments work together and the use of mathematics in science.
- The research is funded by King's College London.
- We are recruiting people who have influenced policy in mathematics and/or science education in recent decades.
- If you agree to take part, you will be interviewed for about 30-60 minutes at a time and place convenient to you. Information collected in this interview will be analysed together with information from other similar interviews. The data will be collated and circulated to all those who were interviewed in anonymised form and you will be invited to comment on it.
- You will also be invited to a focus group at King's College London to discuss issues which have arisen in the interviews and to see if a consensus view can be reached. You will be paid travelling expenses if you attend this focus group.
- Your interview will remain confidential between the interviewer, yourself and the other collaborators in the study.
- You will be offered a copy of any report or paper which is published as a result of this study.
- You will be able to choose to remain anonymous.
- Your interview will be taped and transcribed; this information will be available to: the interviewer; the research supervisor, Prof Justin Dillon; the second supervisor, Dr Anne Bowker.
- This research will form part of the PhD thesis of Victoria Wong and will hopefully be published in peer-reviewed journals and teacher-read journals such as School Science Review.

It is up to you to decide whether to take part or not. If you decide to take part you are still free to withdraw from the study at any time and without giving a reason.

- You may also withdraw any data/information you have already provided up until two months from today: ________________ 2014.
- Interviews will be recorded, subject to your permission. Recordings of interviews will be deleted upon transcription.
- If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form.

If you have any questions or require more information about this study, please contact the researcher using the following contact details:
Vicky Wong,
PhD Student
Department of Education and Professional Studies
King's College London
Waterloo Bridge Wing
Franklin-Wilkins Building
150 Stamford Street
London SE1 9NH
United Kingdom

Victoria.wong@kcl.ac.uk

If this study has harmed you in any way, you can contact King's College London using the details below for further advice and information:
Professor Justin Dillon
Department of Education and Professional Studies
King's College London
Waterloo Bridge Wing
Franklin-Wilkins Building
150 Stamford Street
London SE1 9NH
United Kingdom

[redacted]

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Study: Science and Mathematics Education in English Schools

King's College Research Ethics Committee Ref: REP(EM)/12/13-26

Thank you for considering taking part in this research. The person organising the research must explain the project to you before you agree to take part. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

Please tick or initial

- **I understand that if I decide at any time during the research that I no longer wish to participate in this project, I can notify the researchers involved and withdraw from it immediately without giving any reason. Furthermore, I understand that I will be able to withdraw my data up to two months after the date of the interview _____________________.**

- **I consent to the processing of my personal information for the purposes explained to me. I understand that such information will be handled in accordance with the terms of the UK Data Protection Act 1998.**

- **Please indicate whether you would like to receive a copy of any paper or report published as a result of this research**

Yes	No

- **I would like to remain completely anonymous and I understand that it will not be possible to identify me in any publications**

Yes	No

- **I am happy to be named in any report or article which is published but I would prefer my comments not to be attributed to me**

Yes	No

- **I am happy to be named in any report or article and for any comments I make to be attributed to me.**

Yes	No

- **I agree to be contacted in the future by King's College London researchers who would like to invite me to participate in follow up studies to this project, or in future studies of a similar nature.**

Yes	No

- I agree that the research team may use my data for future research and understand that any such use of identifiable data would be reviewed and approved by a research ethics committee. (In such cases, the data would be identifiable in any report if you have not requested anonymity).

Yes	No

- I consent to my interview being audio recorded.

Yes	No

Participant's Statement:

I - ____ _

agree that the research project named above has been explained to me to my satisfaction and I agree to take part in the study. I have read both the notes written above and the Information Sheet about the project, and understand what the research study involves.

Signed **Date**

INFORMATION SHEET FOR PARTICIPANTS

REC Reference Number: **REP(EM)/12/13-26**

YOU WILL BE GIVEN A COPY OF THIS INFORMATION SHEET

Science and mathematics education in English schools

We would like to invite you to participate in this postgraduate research project. You should only participate if you want to; choosing not to take part will not disadvantage you in any way. Before you decide whether you want to take part, it is important for you to understand why the research is being done and what your participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information.

- The aims of this research are to look at the relationship between mathematics and science in English secondary schools. In this strand of the research we will be looking at schools whose mathematics and science departments collaborate regularly.
- The research is funded by King's College London.
- We are recruiting schools whose mathematics and science departments collaborate effectively; within these we would like to interview the heads of mathematics and science and the headteacher or a member of the senior leadership team, if possible.
- If you agree to take part, you will be interviewed for about 30-60 minutes at a time and place convenient to you.
- Your interview will remain confidential between the interviewer, yourself and the other collaborators in the study.
- You will be offered a copy of any report or paper which is published as a result of this study.
- You and your school will remain anonymous. Your interview will be taped and transcribed; this information will be available to: the interviewer; the research supervisors, Prof Justin Dillon and Dr Heather King.
- This research will form part of the PhD thesis of Victoria Wong and will hopefully be published in peer-reviewed journals and teacher-read journals such as School Science Review.

It is up to you to decide whether to take part or not. If you decide to take part you are still free to withdraw from the study at any time and without giving a reason.

- You may also withdraw any data/information you have already provided up until two months from the date of the interview ____________________.
- Interviews will be recorded, subject to your permission. Recordings of interviews will be deleted upon transcription.
- If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form.

If you have any questions or require more information about this study, please contact the researcher using the following contact details:
Vicky Wong
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London SE1 9NH
United Kingdom

Victoria.wong@kcl.ac.uk

If this study has harmed you in any way, you can contact King's College London using the details below for further advice and information:
Dr Heather King
Department of Education and Professional Studies
King's College London
Waterloo Bridge Wing
Franklin-Wilkins Building
150 Stamford Street
London SE1 9NH
United Kingdom

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Study: Science and mathematics education in English schools

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Thank you for considering taking part in this research. The person organising the research must explain the project to you before you agree to take part. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

Please tick or initial

- **I understand that if I decide at any time during the research that I no longer wish to participate in this project, I can notify the researchers involved and withdraw from it immediately without giving any reason. Furthermore, I understand that I will be able to withdraw my data up to two months from the date of the interview ________________.**

- **I consent to the processing of my personal information for the purposes explained to me. I understand that such information will be handled in accordance with the terms of the UK Data Protection Act 1998.**

- **Please indicate whether you would like to receive a copy of any publication which arises from this study.**

Yes	No

- **I understand that confidentiality and anonymity will be maintained and it will not be possible to identify me in any publications**

Yes	No

- **I agree to be contacted in the future by King's College London researchers who would like to invite me to participate in follow up studies to this project, or in future studies of a similar nature.**

Yes	No

- **I agree that the research team may use my data for future research and understand that any**

  such use of data would be reviewed and approved by a research ethics committee. (In such cases, as with this project, data would not be identifiable in any report).

Yes	No

- **I consent to my interview being audio recorded.**

Yes	No

Participant's Statement:

I -

____

_

agree that the research project named above has been explained to me to my satisfaction and I agree to take part in the study. I have read both the notes written above and the Information Sheet about the project, and understand what the research study involves.

Signed **Date**

Appendix 3: Common questions to policy makers

- From your perspective, when did the STEM agenda first appear?
- Was this when the term STEM appeared too?
- Where did the STEM agenda come from?
- What was the purpose of it?
- What, in your opinion, did it offer to science education?
- What did it offer to [biology/chemistry/physics] education?
- What did the STEM agenda offer to mathematics education?
- Do you think the majority of schools are aware of the 'STEM agenda'?
- From your perspective, what benefits do you think the STEM agenda has offered to schools?
- Do you think the STEM agenda has made any difference to how departments work together in schools?
- What advantages would there be to science departments in schools to working with the other STEM departments?
    - Which departments would it be most advantageous to work with?
    - What might be the benefits to a science department in working with the maths department?
    - What might be the issues?
- What has happened to the 'STEM agenda'? How has it evolved over time?
- The science and mathematics education communities do not seem to work together very closely. Is that a fair assessment or is there closer co-operation which is not obvious?
    - From your perspective, do you think there would be any benefit from them doing so?
    - What do you think would help or enable the science and mathematics education communities to work together?

- The way that mathematics within science or quantitative science in school science is treated has changed over time and the course of the various iterations of the national curriculum.
    - To your knowledge, has there ever been any consultation with the mathematics community or those developing the mathematics national curriculum in the development of those aspects of the science national curriculum?
- From about the mid-1990s the amount of mathematics within science started to decrease. Why do you think this was?
    - What were the advantages of this?
- What were the disadvantages?
- The new draft version of the national curriculum contains a lot more mathematical or quantitative ideas and methods than the previous one. What are your views on that?

Appendix 4: Sample interview schedule for schools

Questions to the mathematics/science teachers

- [Question about their specific collaboration.]
- Could you tell me about some of the things that you have done to implement that?
- How did that get started?
- Why do you do this – it's unusual compared with many other schools?
- What are the benefits to the [maths/science] department of working in this way?

- What differences does your [collaboration] make:
    - to you and your teaching
    - to the students
        - have you noticed any differences in how they approach [maths/maths in science] as a result?
    - to the maths teachers
    - to teachers in other departments
    - to the whole school?

- How much time do you think doing this takes?

- What are the difficulties in trying to do [your collaboration]?
- Is there anything which doesn't get done or is harder due to [your collaboration]?

- How does the [mathematics/science] department collaborate specifically with the [science/mathematics] department?
- Is that collaboration any different to work done with other departments?
- How much time does it take to collaborate with [science/mathematics]?
- What links do you, personally, see between mathematics and science?
- Is everyone in the [maths/science] department involved?
    - Why not?
    - What do you think they lose for not being involved?
- Has this caused any difficulties within or between departments?
- What do you think the next 5 years will look like in terms of collaborating with science?
- Does the senior leadership team here support departmental collaboration?
- What, if anything, has been done to support working across departments?

- What differences do you see in the way in which specific topics are handled within mathematics and within science?
    - Eg data handling, graphing, ratio and proportion
    - Does [your collaboration] help you to understand the differences?

- Is there any further collaboration which you would like to see between specifically maths and science?
- What might you need to make it happen?/What might be the barriers?
- Are there any specific difficulties to maths and science collaborating?
- Any specific benefits to them collaborating?

- The new draft KS4 national curriculum for mathematics states that pupils "should apply their mathematical knowledge to science". What do you think schools can do to ensure this happens?
- The new KS4 national curriculum for science specifies quite a lot of mathematics which has to be used in science contexts. Do you have a view on increasing the amount of mathematics within the science curriculum and in science GCSE exams?
- Will your collaboration help you to implement such changes, do you think?

- Have you done anything like this before somewhere else?
- If you wanted to set up something like this in another school, who would you speak to?
- What advice would you give to someone in another school who wanted to set up a similar collaboration?

Questions to the member of the senior leadership team

- In your school the mathematics and science departments collaborate. This is quite unusual in England. Does the senior leadership team here support the idea of departmental collaboration?
- What, if anything, has been done to support the collaboration?
- Why did the maths and science departments start collaborating?
- What links do you, personally, see between the subjects?
- What differences do you think collaborating makes
  - to the students
  - to the teachers
  - to the whole school?

- How much time do you think the collaboration takes?
- Is everyone in the maths and science departments involved?
  - Why not?
  - What do you think they lose for not being involved?
  - Has this caused any difficulties within the departments?

- What are the downsides to the science and maths departments collaborating?
- Is there anything which doesn't get done because of their collaboration?
- What do you think the next 5 years will look like?
- Is there any further collaboration which you would like to see between maths and science?
- What might you need to make it happen?/What might be the barriers?
- Are there any other departmental collaborations at [your school]?
- Does the school do anything else which is integrated, curriculum-wise?
- Several institutions now offer a physics with mathematics PGCE course. Would you consider employing someone to teach across the two subjects?

- The new KS4 national curriculum for science specifies quite a lot of mathematics which has to be used in science contexts. Do you have a view on increasing the amount of mathematics within the science curriculum and in science GCSE exams?
- The new draft KS4 national curriculum for mathematics states that pupils "should apply their mathematical knowledge to science". What do you think schools can do to ensure this happens?
- Will collaboration help you to implement such changes, do you think?

- What advice would you give to someone in another school who wanted to set up a similar collaboration?

Appendix 5: Sample of coding

This is a section from the interview with MA. There is a response which has simultaneous coding and a section which, although fully coded, has far fewer overlaps.

M feeling excluded / SET to STEM / STEM Sci-focussed

What did linking up with the other STEM subjects offer to maths education?

MA Right well it's a mixed blessing I think as you can imagine, um, to start with I remember being involved with…I can't think which committee I was on at the time but it was um it was a very science-y committee and we'd heard all about the points, I can't remember there's something points that were in each area that were responsible for sort of science CPD and so on…SET points. I remember at every meeting saying maths is supposed to be included in this and where's the maths, I can't see it (laughs).

Sci depends on M

Transition

M in Sci

I think there were probably one or two mathematicians on this kind of very large science group so we did sort of point out that actually science in schools was highly dependent on maths when it came to kind of getting people out into undergraduate degrees and into A-level you actually needed a bit of solid maths there. So I think that it was a logical point to say that if we were having a push on science and engineering that to ignore maths was quite stupid.

STEM↑ £

And of course a funding stream came with that so we wanted to be in on that (laughs).

M service subject?

Danger

M everywhere + important

Is M part of S?

But on the other hand I think it's a mixed blessing because, um, there's a real danger that maths is seen as a kind of small subset of science…that's how the science people see it always…and of course it's much more than that because it's important in finance, economics…using…although I suppose ICT is in with science in a way um but it is a kind of law unto itself. It likes to stand up independently of science so I think we got into it probably because there was a funding stream there if I'm honest. And because it seemed right that you shouldn't talk about science and engineering without maths but I think we've always been aware of this constant danger of being seen only as this little bit within science.

Danger

V *Within a school what do you think the advantage to the maths department would be to working with the other STEM departments?*

Maths is dull

M across other disciplines

M everywhere + important

MA Well first of all there's a real problem that maths is seen… there's a very nice quote in the Cockcroft report which is that maths is not about anything (laughs) and there's a real danger that children see it as a kind of, you know, lots of symbols on paper that you move around with no connection with everyday life. If there're really pushed they can say 'well it can help you in shopping' and that's about as far as you get (laughs). So it is really important that when maths is taught in schools it is taught as something which is really important 'out there'. Of course it's fun to do pure maths, I mean that's nice, but actually we wouldn't have 5 lessons a week or 3 hours a week or whatever it is if it wasn't a big component of other

Appendix 6: Policy makers code book

Name	Description
ACME - composition	This is about the make-up of the ACME committee and who is on it. It includes comments about the differences to SCORE and to individuals on the committee and their impact. It is not about the work of ACME
ACME focus	This is about the aims and work of ACME and its main focus. It includes comments about why science is not the main focus of ACME.
Articulate what maths in science	For comments about what maths is in science, the need to articulate this
ASE	This is for comments about the ASE and what it has achieved and done.
Assessment - as a driver	This code is about using assessment to drive what goes on in school in a positive way
Assessment - difficulties	This code is for the difficulties in assessing certain things in a meaningful way or about the difficulties that there are in the assessments
Assessment - Easier GCSE and A-level	This is about taking things out of the GCSEs and A-levels and about making them easier/more accessible/dumbing down. It is not about 'standards' in general, but very specifically about the ease of the qualifications.
Assessment - no scrutiny	This code is about there being no scrutiny of exams and assessments, about OFQUAL not having any bite and there being no-one who really looks after these things
Authentic experience	This code is about maths needing to be in science to give an authentic experience of science. It includes comments about the wrong impression being given when maths not in science.
Baccalaureate and other changes to the structure of schooling	This is about suggestions for baccalaureate, wider curriculum, changes to schooling and examination structures mentioned. It is not about GCSEs and A-levels and the problems with them specifically.

Barriers to school departments co-operating: time	This is about time as a constraint in people collaborating and time being needed for good quality collaboration and working relationships. Also for time being needed in development of criteria/NC etc. This is not about the original NC which has its own time code
Beliefs	for comments about beliefs/believing in collaboration/effect of beliefs on practice
Biology issues	This is for comments around the place of biology in the STEM agenda, mainly that it didn't have much of a place. Also for other comments relating specifically to biology
Bits of history	This is for interesting bits of historical information that don't at the moment seem to fit into one of the other codes. They may or may not prove to be relevant
Careers, jobs and advice for students	About careers for students, careers advice, jobs and future paths
Change maths to suit science	For comments about how maths could or should change to suit the needs of science
Collaboration other than school or community	This is for examples of collaboration mentioned by interviewees which were not school or community wide collaboration but in other organisations eg QCA
Concern about standards	This is about concern about standards in science and maths or STEM subjects. It includes comments about things which might detract teachers from their focus on standards. This is not about poor attainment in maths or science
Confidence	Confidence and the lack of confidence - particularly relating to maths and science and the confidence in the other subject
CPD for teachers	This is about CPD for teachers, comments on the need for professional development, comments on increasing access to PD, issues with it, anything to do with CPD. It is not about getting teachers in or teacher numbers.
Creativity	For comments about creativity coming from blurring boundaries between subjects. Links to Motivating students

Curriculum and classroom practice different	For comments about knowing one but not the other or general comments about them being different
Curriculum prevents closer working	For comments about separate curricula, separate exams keeping departments from collaborating
Danger	Talk of danger, risk and similar to getting involved with something
David Sainsbury	This code is for comments about David Sainsbury and his influence
DFE have M and S links	For comments about the Department for Education having links between maths and science or having joint teams. Not for comments about high level strategy group which is separate code
Diversity	For any comments about diversity, issues with diversity of any kind
Double GCSE in maths	This is about the idea of having two GCSEs/linked pair for maths as standard as it is a big subject.
Economic argument	This is for the economic arguments around the national skills shortage, economic reasons why the country needs stem graduates/A-level students
Examples of consultation between science and maths	For examples where maths and science have consulted each other
Figures of speech	This is for figures of speech that people use - but only for mathematical and scientific ones. including analogies and similar
GCSE criteria	This is for comments about GCSE criteria, about them being separate from the NC KS4 PoS
Good teaching	This is about the importance of good teaching, in any subject and at any level.
Government likes maths	This code is about the current government being keen on maths
Government policy effects	This is about the effects of government policy. It includes comments about policies having no effect or impact. It is not about making or receiving policy.

Government policy making	This is about how government policy is made, decided. It may be specific examples, may be talking about it being cloudy.
Government prefer maths and science separate	For comments about the government preferring maths and science to be separate, importance of separate subjects and not liking inter-disciplinarity
Great quotes	Mixture of quotes but all worth noting. This is a mixed bag, not to be analysed, but anything goes
Hard to join up maths and science	For comments about it being difficult to bring maths and science together
Importance of success for students	This code is about the importance of success for students. It is not about lowering standards but about all students being successful
Independent school advantage	This is for comments that people make about the advantages and privileges of independent schools including in terms of the numbers who go on to do STEM subjects at A-level and university level
Individuals	This is about the impact and effect that individuals can have on the policy making process. Some specific individuals have their own codes.
Interdisciplinary or cross-curricular	This includes comments about interdisciplinary and cross-curricular work it includes problems and challenges as well as positive comments made about cross curricular work
International comparisons	This code is for comments about international comparisons data being used. Includes any comment about international, PISA, TIMMS, government comparing us to overseas
Jealousy of subject territory	This code is where it seems like people are defending their subject territory, comments about territory being taken over, comments about encroaching.
John Holman	Comments about John Holman and what he achieved
Joining up across curriculum subjects	This is for comments about joining up across curriculum subjects rather than cross curricular. It includes the difficulties of joining up across the science subjects, not just across maths and science.

Lack of knowledge of other curricula	For comments about science not knowing maths curriculum and vice versa. Not for comments about how they should know other curricula (separate code)
Language difference between maths in maths and maths in science	This is about specific differences people note in the way that mathematical concepts are used and talked about in maths and in science, and the difficulties that this could cause for students. Also about terminology differences across science subjects and awarding bodies
Level of difficulty	For comments about what level of difficulty is appropriate for students, particularly with respect to maths in science
Maths - across other disciplines	This is for comments about numeracy across the school and in other school subjects. It is not specifically about maths and science but about numeracy and maths in other subjects at school level and beyond
Maths - taught badly in science	This is about how maths is taught in science. Invariably they are about how maths is taught badly by science
Maths and Sci programme boards	This is comments about the maths and science programme boards and bringing them together. It includes comments about what they do, concerns about bringing them together, composition of them. It does not include comments about the STEM programme board/higher level strategy group
Maths and science communities very different	For comments about how the maths and science communities are very different.
Maths at KS5	This includes comments about maths at KS5 including comments about destinations, choices, issues. It does not include anything about numbers at KS5
Maths can be lost in interdisciplinary work	For comments about maths being lost, subsumed or not focused on in interdisciplinary contexts

Maths feeling excluded	This is for comments about maths being excluded from things. Not specifically about SET to STEM (separate code) but about feeling excluded, or about now being included.
Maths in engineering	This is about the use of or need for maths in engineering, the links between maths and engineering.
Maths in physics	This is for comments relating particularly to physics and the distinctiveness of the issue of maths in physics rather than science
Maths in science	This is about maths being in science at school level or in general. It is not about scientists using maths (separate code) but about science as an entity using or needing maths.
Maths is difficult	Maths is difficult - not about attainment or standards or it being everywhere, but about it being hard.
Maths is dull	This is about the problem of lack of student interest in maths, what needs to or can be done to increase it, the difficulties of motivating students to want to study maths.
Maths is everywhere and important	This is about maths everywhere, maths all around us. It is not about maths in other specific disciplines. It also includes comments about the importance of maths and it's high place in the hierarchy of subjects
Maths is it part of science	Comments that link maths with science, specifically saying that maths is a part of or sub-set of science, or comments that it shouldn't be seen as that
Maths not service subject	This is for codes about maths not wanting to be viewed as a service subject and maths not being about serving the needs of other subjects but as important in its own right.
Maths taken out of science	This is for codes describing how maths has been taken out of science and some of the possible reasons for that
Maths teachers should understand maths in curriculum	About how maths teachers have a professional responsibility to know how maths is used across the curriculum.
Minimal consultation	For any discussion about lack of contact between communities about any aspect of education.

between science and maths	
Motivating students	This code is about motivating students and ideas for motivating students, the need for motivating students and suggestions for things which do motivate them. It is not about standards or attainment.
Mutual benefit	The idea that both maths and science in schools would benefit from collaboration. This is just about schools.
National Skills requirement	This includes comments about planning for the national skills requirements, skills shortages, need to bring in overseas people, pipelines. It does not include comments about A-level numbers or economic need for the country
National strategies	This is for comments about the national strategies - stresses, strains and achievements
NC - science writers know maths	For comments about science NC writers knowing maths with the implication that they do not need to consult maths.
NC changes	This code is about changes to the National Curriculum. It is not about collaborating across the subjects and it is not about putting together the original national curriculum
NCETM	Comments about NCETM, including it being a positive outcome of the STEM agenda for maths, about it being smaller than science and the reasons for this.
No point to closer working	For comments about there being no point in trying to get departments to work together more closely
Not interdisciplinary in schools	Subjects by specialists - not interdisciplinary teaching in schools. Keep subjects separate in school, link up later
OFQUAL	For comments about OFQUAL and their influence, strengths and failings
OFSTED and accountability measures	This is about OFSTED and assessing schools. It includes accountability measures and the differences in what OFSTED are looking for in maths and science departments and the impacts this can have.

Order of maths and science	For comments about the order of maths and science - particularly how it does not have to be maths first
Original national curriculum committee	This is about the original NC committee and who was on it
Original NC civil servant involvement	This includes comments about the original NC and how the civil service were involved
Original NC relationships between maths and science	This is about the relationships between the maths and science committees and programmes of study
Original NC speed and time	These are comments about putting together the original NC and it being a rush job
Pipeline and education	For comments about pipelines and education
Poor or low attainment in maths	This is about poor or low attainment in maths, nationally, individually and concerns about it. It includes comments about the impacts on individuals and the country of poor attainment in maths
Pre-National Curriculum	This is about comments about life pre-national curriculum. It includes things about numbers before NC, not taking balance of subjects, gender imbalance and such things. Numbers from then go in here not in student numbers bit.
Pre-STEM Developments	This is for comments about developments which became STEM but which preceded the term. It isn't about the history of the term STEM but the history of the ideas which STEM may be based on.
Primary	This is about comments on primary maths including how it is integrated with science, issues with primary maths, anything relating to pre-secondary maths. Also comments on primary science
Public understanding of science	This code captures concerns about public understanding of science. It is often about the limited nature of public understanding and what needs to be done about it. It does not include the science for public understanding A-level

Put students off	Too much maths might put students off - comments around that, students not liking maths and this might make them not study science
QCA role	for all comments about the role of curriculum organisations in their various guises - NOT just comments including QCA or about their existence, but their role in curriculum
Reasons for adding in maths not always good	This is for comments about the agenda behind the addition of maths and concerns about it.
Relationship between science and maths	This is about relationships between the maths and science communities and learned societies. Includes engineering.
Relationships between maths community	This is comments about the relationships between the maths community and within the maths community, about the different organisations that make up maths and the numbers of organisations that there are. it is not about relations between maths and science
Relationships between science community	This is about relationships within and between the organisations of the science community: the learned societies, charitable trusts and other interested bodies. It is not about relationships between science and maths
Role of professional associations and learned societies	This is for comments about the role of professional associations and learned societies in policy development and in collaboration
School collaboration is rare	For comments about how collaboration across maths and science is rare and unusual
School departments collaborating	This is for comments about school departments collaborating. It may be the need for collaboration or the difficulties with collaboration or incentives to encourage collaboration.

School leadership and management	For comments about school leadership and management and the role they might play in collaborations
Science as context	This is about science being a context in which to do mathematics. It includes in the real world and in school.
Science depends on maths	This code is for comments about how science is dependent on maths or how maths is v important to science. Including maths is the language of science
Science needs to teach the maths themselves	This is about examples and suggestions that science (at whatever level) needs to teach the maths. Includes university level, school level,
Science or BCP	For comments about science being formed of bio, chem, phys and the difficulties that can lead to
SCORE	This is for comments about SCORE and what it has achieved, particularly in bringing together the science community to have single voice. All comments about what SCORE is and what it has done go in here
Separate sciences	This is for comments about separate sciences, triple award. The advantages and disadvantages for having separate sciences, proportion of curriculum time.
SET to STEM	This is about the change of name from SET to STEM, including the renaming of organisations to reflect the name change. It does not include comments about the programme boards.
Silos or divisions between subjects	This captures discussions about subject boundaries, division, silos, artificial barriers, talk of social constructs and the problems that such boundaries cause
SLCs	This is about the science learning centres, the national science learning centre: their set-up, their funding, their achievements, their problems
Statistics important but	This code is about statistics and data and how statistics is treated in school maths and across the other subjects

poor in curriculum	
STEM - Broad agreement with aims or subject grouping	For positive comments about STEM and its aims, or the grouping of those subjects
STEM - disconnect between inside and outside school	For comments about STEM being different inside and outside school/education
STEM - links or integration	For comments about whether STEM is or should be about links or integrating to form something new
STEM - No point to term	This captures attitudes to STEM that suggest that there is no point to having the term or it is not helpful. Also includes not liking the term STEM and reasons for that
STEM - often E&E	This code is about STEM often coming down to being something added on, enrichment and engagement. Anything about STEM enrichment and engagement should go in here
STEM - science focussed	For comments about STEM being focussed on science, particularly contrasted with maths, but also T and E.
STEM - Technology and Engineering	For comments about the T and E in STEM
STEM £	This is for comments related to money given to STEM, funding, distribution of funding. It is not about economic arguments for more graduates/A-level students
STEM £ disparities in funding	For comments about disparities in funding between disciplines within STEM
STEM £ fights over	for comments about fighting over £ within STEM
STEM £ increased	for comments about financial benefits of STEM

STEM £ spending should be more focused	For comments about how STEM was about focusing spending more carefully
STEM about uniting subjects or organisations	This is for where people think that the aim and purpose of STEM was to unite the subjects and bring them together or bring together the subject organisations
STEM achievements	this is about positive achievements of the STEM agenda
STEM agenda not helped science and maths in schools to work together	This is for comments that the STEM agenda has not helped maths and science departments in schools to work together
STEM changes and future	This is for comments about the STEM agenda slowing/stalling/losing pace under the current government. It is not about criticisms of the STEM agenda per se. Also other comments about potential future of STEM, particularly when not overwhelmingly positive
STEM didn't achieve much	This code is for comments that suggest that STEM didn't achieve very much, not much or nothing. Also for comments that strands or aspects of it were not very effective.
STEM gave increased access to government	For comments about STEM increasing access to decision making sites of government, particularly for closely involved organisations
STEM gave increased status	This is about STEM giving an increase in status to the STEM subjects (or some of them). It is very specifically for comments about status or equivalents - it is not about having a louder voice when you all speak together
STEM higher level steering or strategy group	This is for comments about the higher level steering group - not the programme boards.

STEM in schools	This is about STEM in schools. It is not about relationships between departments but about how STEM is viewed - or not - in schools
STEM is maths and science	This is for the argument that actually STEM is maths and science and that the T and the E are not important. It includes the argument that STEM is maths and physics although this may be separated later
STEM not from education community	For comments about STEM not coming from education community
STEM offered engineering nothing	This is about STEM not really doing anything for Engineering and technology
STEM offered maths nothing	This is about STEM not offering anything to maths, or not as much as science. Includes comments about it offering very little.
STEM programme	This code is discussion about the strands of the STEM programme and what they were
Student numbers	This is about A-level and university numbers and any comments relating to student numbers, maths, physics, other subjects but numbers of students.
Students don't see the links	for comments about students not seeing the links between maths and science
Teacher numbers	This is for comments about teacher numbers, teacher recruitment related to numbers including maths, science and STEM teachers
Teachers don't see the links	This code is for comments that teachers don't see the links between the subjects (not for comments about SLT/SMT) and also for comments that if teachers can't see the links what chance is there of the students doing so.
Teachers unpick joined curricula	For comments about teachers unpicking linked curricula to make it more teachable
Technology curriculum links	About linking technology to other curriculum subjects (mainly STEM subjects)
Tension between government	This is about the mis-alignment of government policy and the STEM agenda. It is not about government policy per se but only about the tension between it and STEM

education and STEM	
Time	Time as a limiting factor to collaboration or other working together
Transfer	for comments about transferring knowledge between particularly maths and science
Transition between phases	This is about the difficulties students have transitioning between primary and secondary, secondary and tertiary GCSE and A-level and any other transition. It includes suggestions to help the transitions. It is not about the qualifications themselves or content or numbers
When did STEM appear	This is comments about dates and when STEM first appeared. It does not include comments about SET to STEM
Where to put this	This is for comments that I think are worth coding but I can't quite fit them into my current codes. If there are enough similar ones I will generate a new code
Whole curriculum	for comments about the whole curriculum, the curriculum in total rather than individual subjects - or about the lack of a whole curriculum and the issues that this causes including the government's lack of enthusiasm for joined up or whole curriculum
Wider population ability now	This is about the change from having only top %age of pupils studying maths and science to it being science for all and the consequences of that.

Appendix 7: School data code book

Name	Description
Apply mathematical knowledge to science - how schools can do it	Responses to how schools can help pupils apply their mathematical knowledge to science
Blame and expectations	About maths blaming science and science blaming maths for difficulties that students have using maths in science
Collaborating - projects	For details about projects and specific comments about projects
Collaborating - trips	For comments about collaborating on, with or via school trips and outside school activities. From including members of departments in each other's trips to joint trips
Collaborating an added extra not a priority	This is for collaboration being an added extra not a priority, not part of the usual day to day business of teaching and getting good results
Collaborating changed my teaching	Descriptions of how collaborating across departments has changed teacher practice
Collaborating visiting expert	About the visiting expert model where one subject teacher visits another subject lesson
Collaboration - projects difficult for less able	Quotes about collaboration and projects being of more benefit to higher ability pupils or difficult to access for least able
Collaboration - via curriculum and SoW	For collaboration in terms of Scheme of Work and curriculum rather than an added extra
Collaboration benefits staff	This code is for ideas and comments that collaboration benefits staff eg by increasing enthusiasm or upskilling them
Collaboration benefits students	This code is for student enjoyment of collaborative teaching and added incentives for children to do well when departments collaborate and other benefits to students mentioned
Collaboration is good practice and normal school practice	For comments about collaboration being part of being a good sci/M teacher. Improving teaching. Good practice. For collaboration being part of what the school considers normal practice rather than an add on

Collaboration through informal conversations	About how chatting and informal chats can be part of collaboration
Collaboration to support specific students	About collaborating/discussions to help specific student difficulties
Collaborative teaching makes it hard to take indiv subj to high level	This is for comments that working by joint project and collaboration makes it hard to take individual subjects to a high enough level
Curriculum change	For comments about changes to the curriculum - speed, frequency, other comments about curricular changes
Curriculum does not link	For comments about curricula not linking up across key stages and subjects
Different style teaching for projects	Description of different teaching styles used for MS collaboration or projects
Difficult to evaluate collaborative teaching	This is about it being difficult to evaluate or measure the success or otherwise of collaborative or cross curricular teaching and learning. Talk about skills pupils develop that aren't measured.
Does anyone teach both M&S	Responses to this question or spontaneous discussion of teachers teaching both
Doing STEM in schools	For comments about what STEM is in schools/how STEM is interpreted/how STEM is 'done'
Don't overburden teachers	This is related to time but about comments for teachers being tired and extra things should not overwhelm them
Equality and equity	Comments for MS collaboration helping or aiding equality and/or equity
External pressures acting against collaboration	This is for pressure of exams, government pressures, accountability measures acting against collaboration. Not for Ofsted, separate category.
External stimulus	Working together coming from a stimulus from outside the departments - either external to the school or from the school but outside the departments.
Faculty of science and maths (or STEM)	For comments about schools having a faculty which cuts across both science and maths and the consequences of that

Freedom	For comments about constraints when there is formal collaboration and the reverse. For comments about teachers valuing freedom and for when formal collaboration reduces freedom
Good relationships between staff in M&S	This is about how collaboration is aided by positive relationships between staff, particularly Heads of Dept
Grades and outcomes	Particularly comments relating to whether collaborating improves grades - or reduces them
Hierarchy	For comments about school hierarchy
Importance of curriculum	For comments about how it is important to get the curriculum right
Importance of mathematics to students' life chances	For comments about the importance of maths to students' life chances
Importance of STEM subjects to students' life chances	For comments about the importance of STEM subjects to students’ life chances. NOT comments about importance of maths to students’ life chances (separate code)
Independent schools have freedom	This is about how independent schools have more freedom which can make it easier for them to promote collaboration
Interesting - don't know where to put it	As it says. Will be divided later if multiple comments on same topic.
Joint meeting of benefit	For comments about joint meetings between departments being beneficial
Key person	Talk of a key or keen person to organise collaboration. Maybe from each department
Knowledge of other curriculum a limitation	This is for comments about lack of knowledge about the other curriculum being a limiting factor in the collaboration - probably links to KS3 collaboration being more popular. Also comments about how to improve knowledge of other curriculum
KS3 collaboration	This is for comments relating to collaboration being easier with younger pupils or it being more preferable to collaborate at KS3
Language differences and issues	Descriptions of difficulties with language between maths and science and just the differences between the two

Language differences in the curriculum - examples	For language differences that are in the curriculum so would be very difficult for schools to change - or where teachers believe this is the case. Specific examples.
Less now than last year	This code picks up comments that schools are collaborating less now than they used to
Links between maths and science - examples	Examples given of mathematics which is used in science
Literacy a higher priority than maths	For comments about literacy being higher priority than numeracy or maths across the curriculum. Also for comments about focus on literacy being detrimental to numeracy
Logistical difficulties with projects	Talk about logistical difficulties with projects - not about staff views or staffing issues, just logistical ones
Making maths explicit helps students understand the science	This code is about how making the maths explicit helps students to understand the science
Maths as service subject	For comments about maths as a service subject - or not, but using term service subject or similar
Maths dept don't know how maths is used elsewhere	For comments about maths department not knowing how maths is used in other subjects and departments
Maths gains from working together	This is for comments about the maths being helped by showing students the links or by collaborating. Includes examples from science being used in maths and showing real life uses of maths through science
Maths is more than links to science	For comments about maths having links to wider subjects than science and possible issues if there is a focus on science. Also for comments about maths for its own sake.
Maths skills a limitation on science learning	For comments about how students' maths skills limit their learning in science
Maths teacher background makes a difference	For comments about maths teacher background and how that might impact on who and how they want to collaborate

Maths teachers do not all teach the same way	This is for comments that maths teachers teach maths in a variety of different ways and this varies according to the groups that they are teaching
Maths teachers struggle to teach science	Comments about how maths teachers may find science teaching difficult because of e.g. the safety and practical aspects or subject matter
Mismatch in expectations	For comments that there are mismatches in what children are expected to be able to do in other subjects and compared to what they have achieved in maths
More maths in science	Comments about the increase of maths in science curriculum
Need to have teachers on-board	For comments about the need to have teachers on-board in any initiative and not to impose it on them
Not all staff involved	Not all teachers in each department are involved
Numeracy and mathematics	For comments about the relationship between numeracy and mathematics
Observed lessons	For comments about observing lessons, particularly across subject boundary
OFSTED	For comments about OFSTED and its impacts
Order of teaching	For comments about teaching order and potentially changing teaching order of material in maths/science to help other subject
Other collaboration	Descriptions of other collaborations within the school or that the individual staff have been involved with in other schools
Ownership of collaboration	This code is for comments about who owns projects or collaborations. Eg 'it is our project'
Parent and pupil expectations a barrier	Parents and pupils expect the subjects to be separate so putting them together is a barrier to be overcome
Physical proximity and spaces	This code is for talk about the physical proximity of departments allowing or limiting collaboration
Physics has closer links than other sciences	For comments that mathematics is more closely linked to physics and of more interest to physicists than other scientists AND comments about physics and maths in general
Resources	For comments about how resources or the lack of them can hinder or aid collaboration

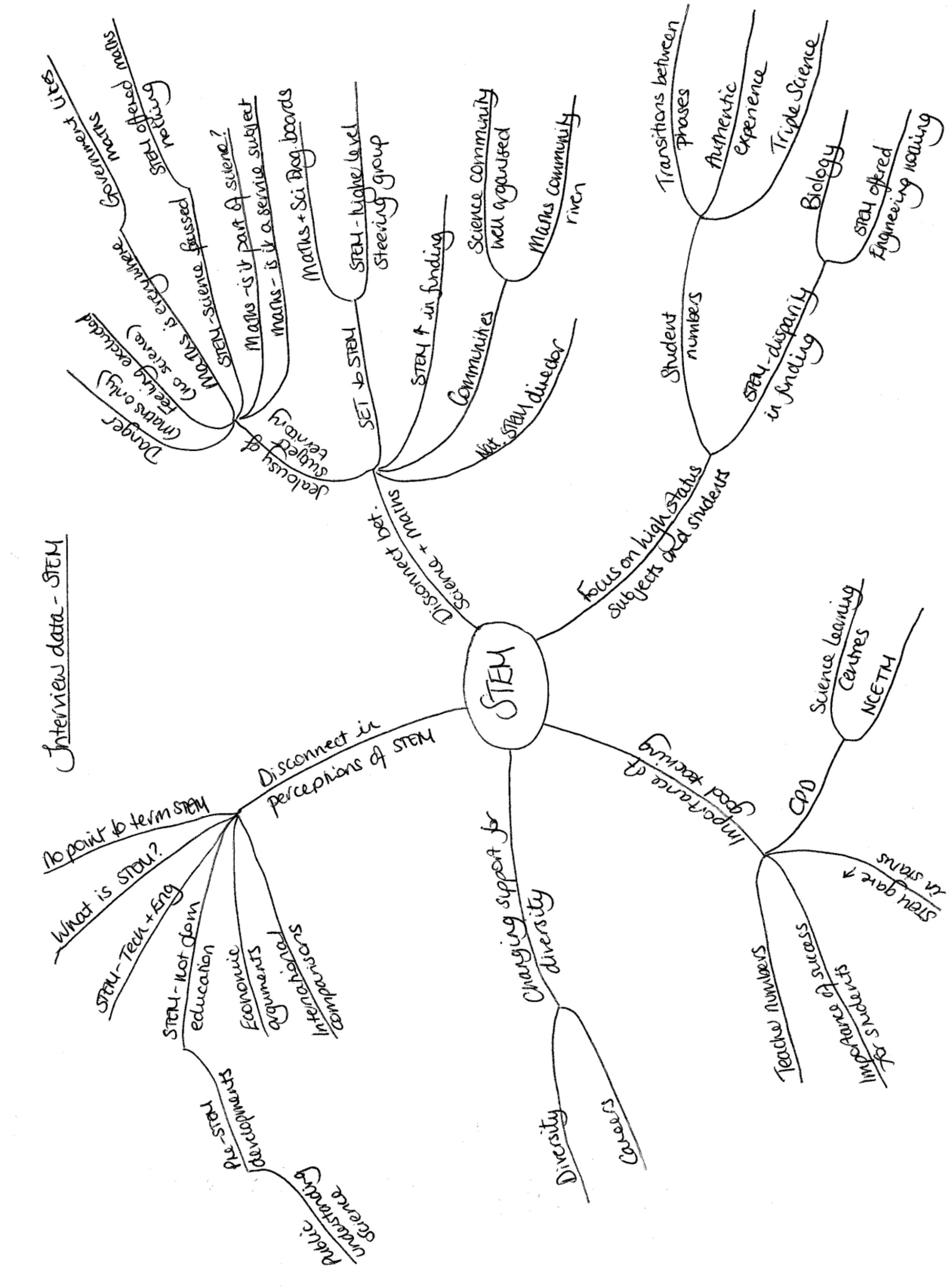
S and M different priorities	About how sci and maths have different priorities for teaching and learning
Science as context for maths	For where science could or has provided maths with a context for what they are doing or provided data or examples
Science dept get help from maths	Comments about how maths dept help the science dept with aspects of teaching the mathematical parts of science - NOT science saying what extra help they would like (separate code)
Science do not know how maths is taught	Science teachers do not know how maths is taught, partly as maths teaching has changed
Science do not teach maths well	For comments about how science do not teach maths well or teach it in a very algorithmic way
Science staff lack confidence with maths	This is for comments about science staff lack of confidence with maths - and more general comments about staff difficulties with maths
Science teach the maths	This code is about the science department having a responsibility to teach the maths (and literacy mentioned too), that it is not just the responsibility of the maths department. Also needing to teach the maths if required before taught in maths
Senior leadership team	For comments about senior leadership team, their background, their views of maths/science
Setting different in M and S	For comments about how the sets in maths and science are different. This may be a barrier to collaboration, may make projects harder
Sharing of practical resources	For comments about working with science being of benefit when doing practical maths and vice versa. Anything about resource sharing, including technician sharing
Small scale collaborations are best	For comments about how small scale collaborations are the best - this may be projects, may be Visiting Expert or may be something else; but small scale
Small school, fewer staff = easier to collaborate	this is about small schools finding it easier or fewer staff involved making it easier
Some teachers do know maths and science	Code for comments about teachers who are comfortable with both maths and science and who know both

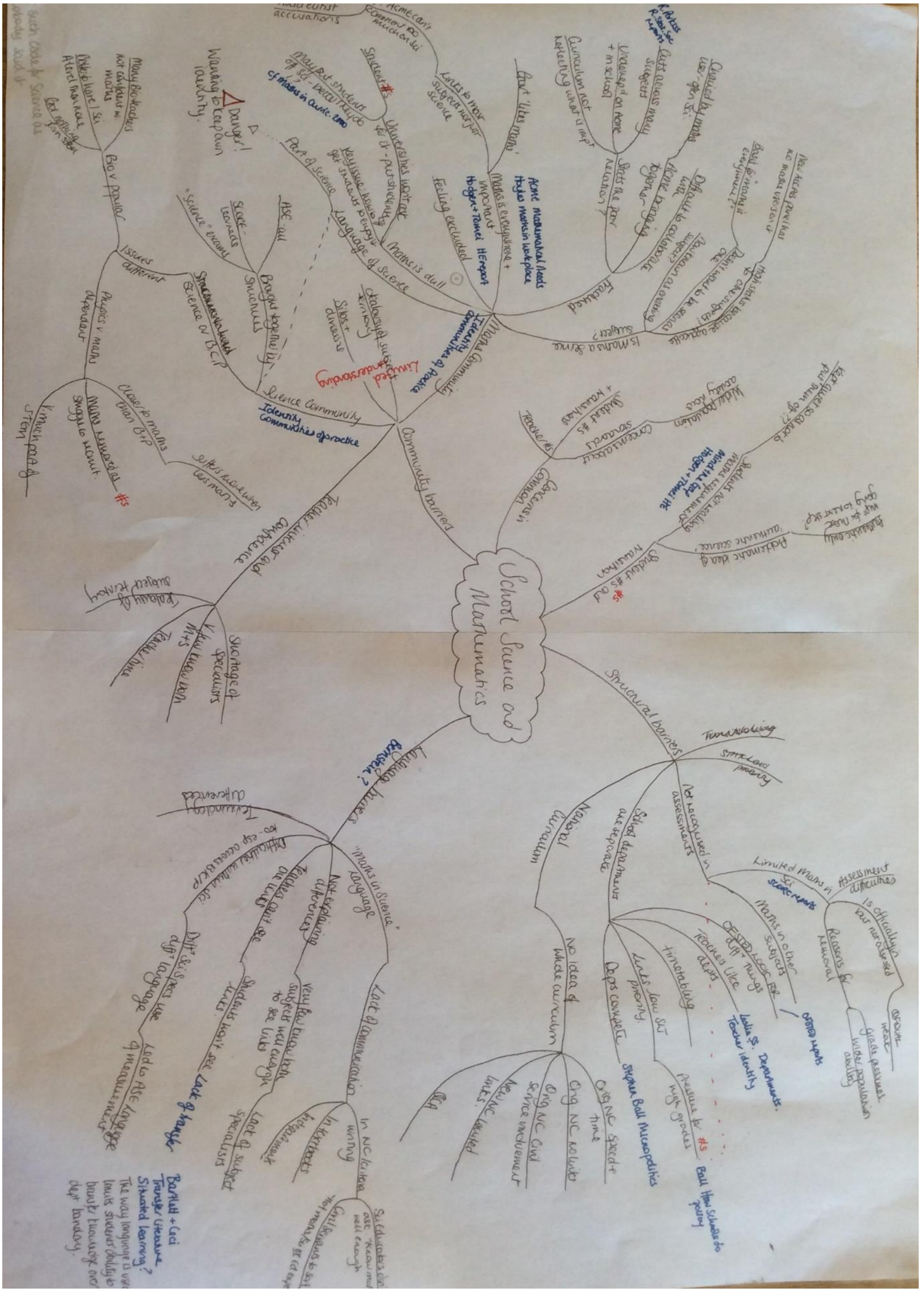
Specialist teacher skills are of value	This code is about the specialist skills that teachers have and how that is valuable - to contrast often with them not having those skills for every subject
Staff complaints, concerns and issues	This code is for staff complaints and reservations about collaborating or not doing what has been agreed
Staffing	Descriptions of staffing, staffing issues, keeping staff, recruitment and the constraints that staffing issues can place on departments
Stay in own world	This code is about collaboration which allows the teacher to stay in their own world eg even when visiting another class - teacher feels more comfortable
STEM clubs for limited numbers	This code is about STEM clubs being for the minority
Struggling students can find integrated teaching difficult	To capture the issues that students who find learning difficult can have with integrated teaching
Students as source of information about differences	Students saying that they do not do 'it' that way in maths or vice versa or in some other subject.
Students can ask maths teachers about science	Comments about students being able and willing to ask maths about issues with maths in science - and maths being willing to help them
Students claim not to know the maths	Comments about students saying that they have not done any necessary maths
Students do not see the links	This is for comments about students not seeing the links between maths and science in school or elsewhere.
Students excited to stop collaborating and do separate subjects	This code is about students looking forward to doing separate subjects when all they have done up to this point is joint STM curriculum, usually in y9
Students find maths difficult	This code is for comments about students finding maths difficult and also for teachers not appreciating how difficult kids find it - especially non-maths teachers
Students find maths frightening	This is for comments about students being nervous or scared or freezing when it comes to the mathematical content of science

Students helped to see the links	this is about students being helped to see the links between M and S
Students make links spontaneously	How the collaboration helps students to make the links between the M and S
Students surprised	For comments about students being surprised by collaboration and by teachers knowing about the other subject
Subject boundaries are artificial	Comments about subject boundaries being created (perhaps for a reason) and being artificial
Teacher beliefs	This code is about the philosophical difficulties and disagreements with cross curricular teaching and teacher beliefs about it
Teacher confidence	For comments about teacher confidence limiting collaboration or willingness to engage with the other subject or comments about needing to improve teacher confidence
Teacher development and CPD	This code is about the need for teacher development and/or CPD if teachers are going to deliver projects in what might be a different style of teaching
Teacher involved gets something out of it	For comments about what the collaborating teacher gets themselves from collaboration. Eg material for Masters thesis/enjoyment/…
Teachers don't know the links and differences	This is about how teachers do not know the differences between the maths and the science and don't know the links. It is also about how collaborating has helped teachers to learn more about the links and differences
Teachers don't want to teach out of subject area	This is what it says - comments about teachers not wanting to teach out of subject area
Teachers in different departments do not know each other	Teachers in different departments don't know each other. This is just as a fact and also as a limitation to working together
Teaching outside subject area is hard	This code is for acknowledgements that teaching outside one’s own subject area is hard - separate codes for specific comments about M and S teachers
Tension/protection	This is about people being protective of their subject territory
Time	This code is about time constraints and about collaborating taking a lot of time - or not a lot of time. Any comments about time

Time saving	The idea that working together saves time - usually in the classroom in an overcrowded curriculum.
Timetable and setting	Constraints or issues or comments related to the timetable and setting and how they affect what can be done with collaborating
Transfer as problematic	This code is for transfer being problematic and the difficulties which occur when students do transfer between m and s but don't understand the differences
Triangles	for all comments about formula triangles
Understanding across departments improves	This is about how collaborating allows teachers across departments to understand each other more
Very few teachers have skills to teach M&S	This is about few teachers having the skills to teach across M&S especially to KS4. Similar to codes about M teachers not able to teach S and vice versa

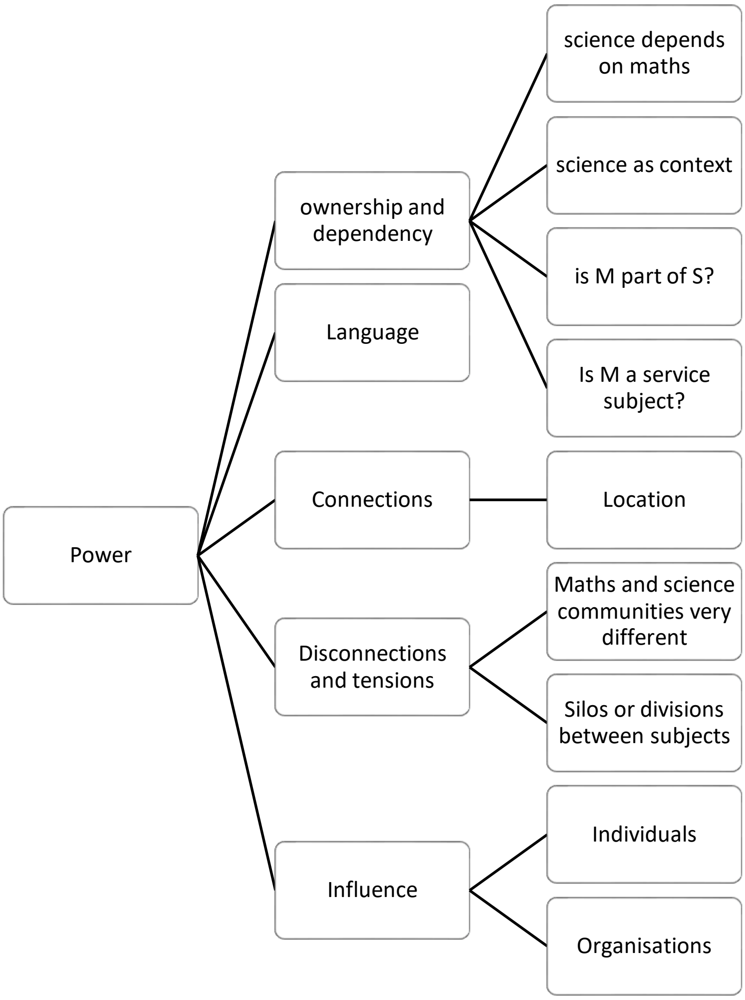
Appendix 8: Mind-maps from early in the analysis

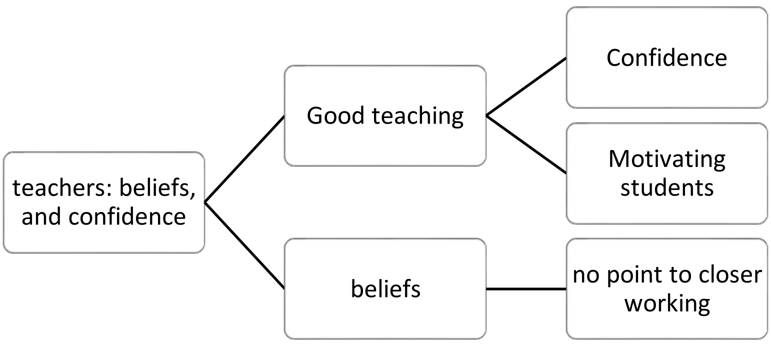


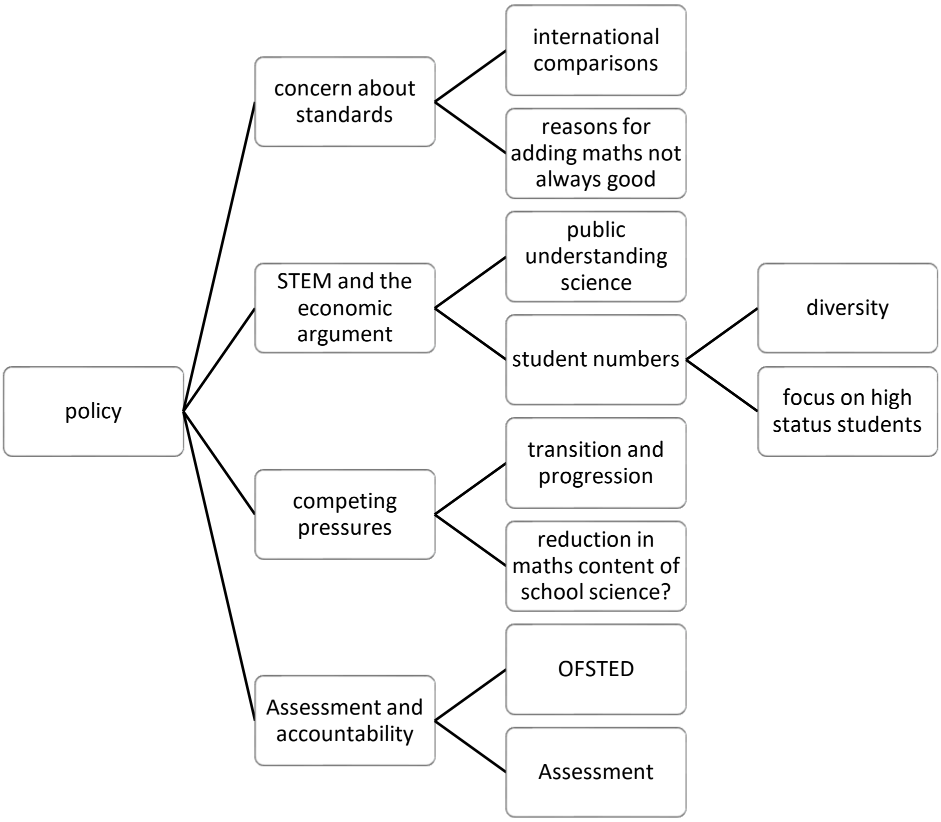

School Science and Mathematics
Structural barriers
Community barriers
Language barriers
Science Community
Maths Community
Maths is dull
Language of Science
Feeling excluded
Frustrated
National Curriculum
Timetabling
Lack of communication
"Maths in Science" language

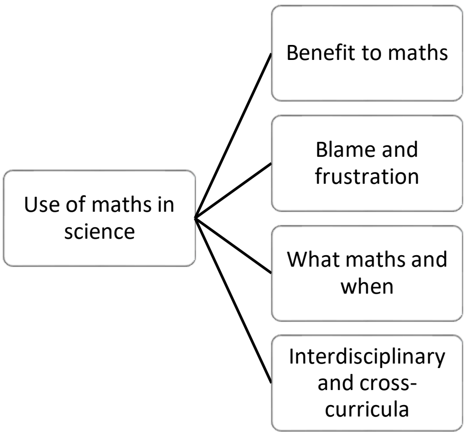
Appendix 9: Coding trees from later in the analysis

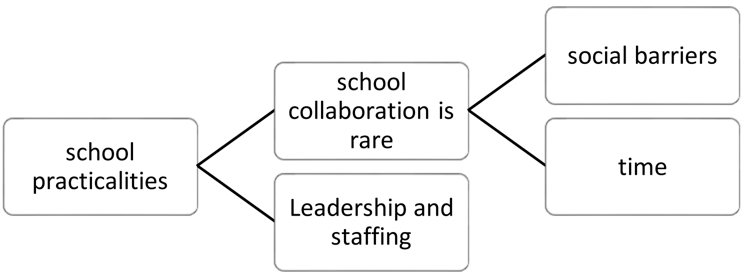
Policy makers code tree



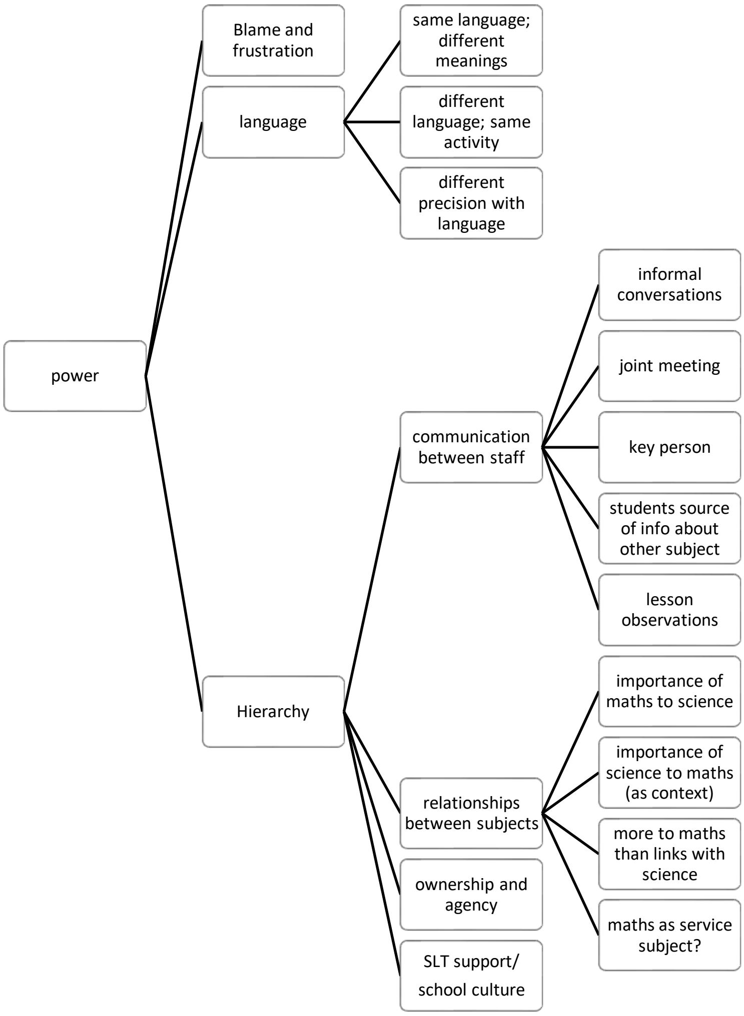


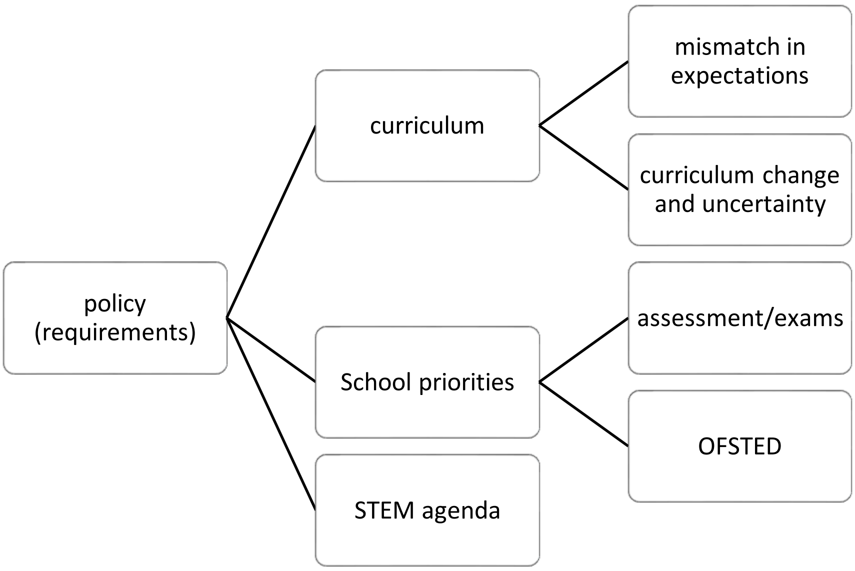

policy
concern about standards
international comparisons
reasons for adding maths not always good
STEM and the economic argument
public understanding science
student numbers
diversity
focus on high status students
competing pressures
transition and progression
reduction in maths content of school science?
Assessment and accountability
OFSTED
Assessment

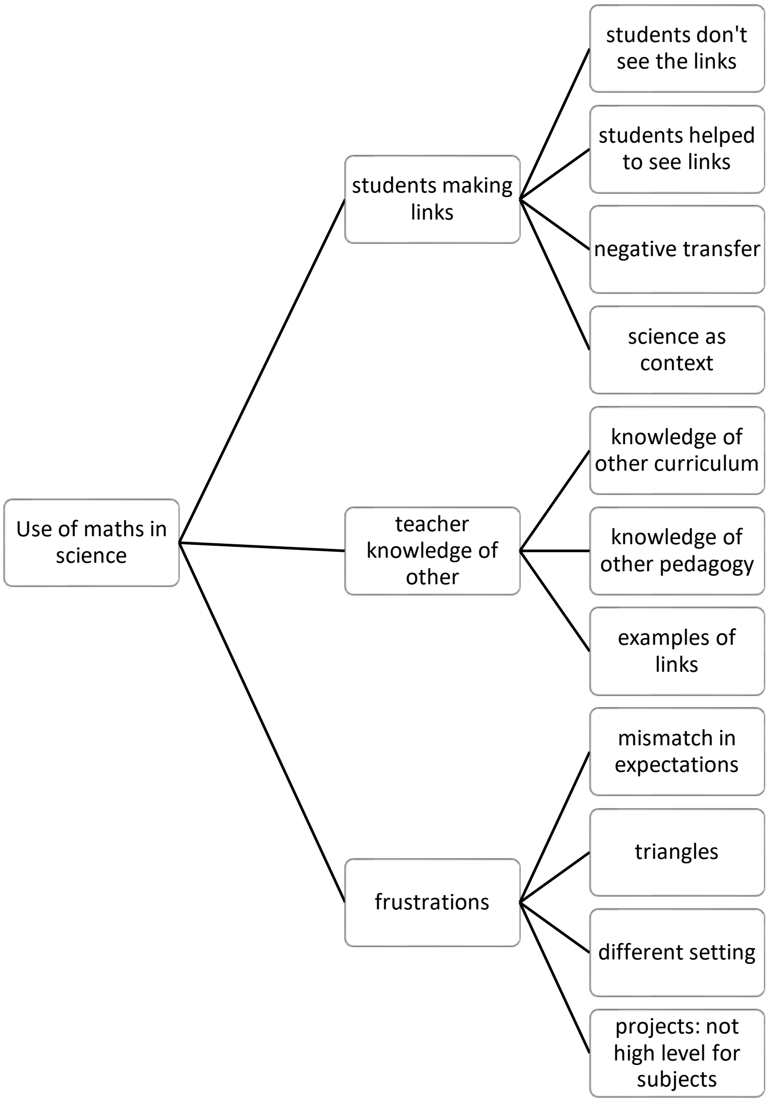

Use of maths in science
Benefit to maths
Blame and frustration
What maths and when
Interdisciplinary and cross-curricula

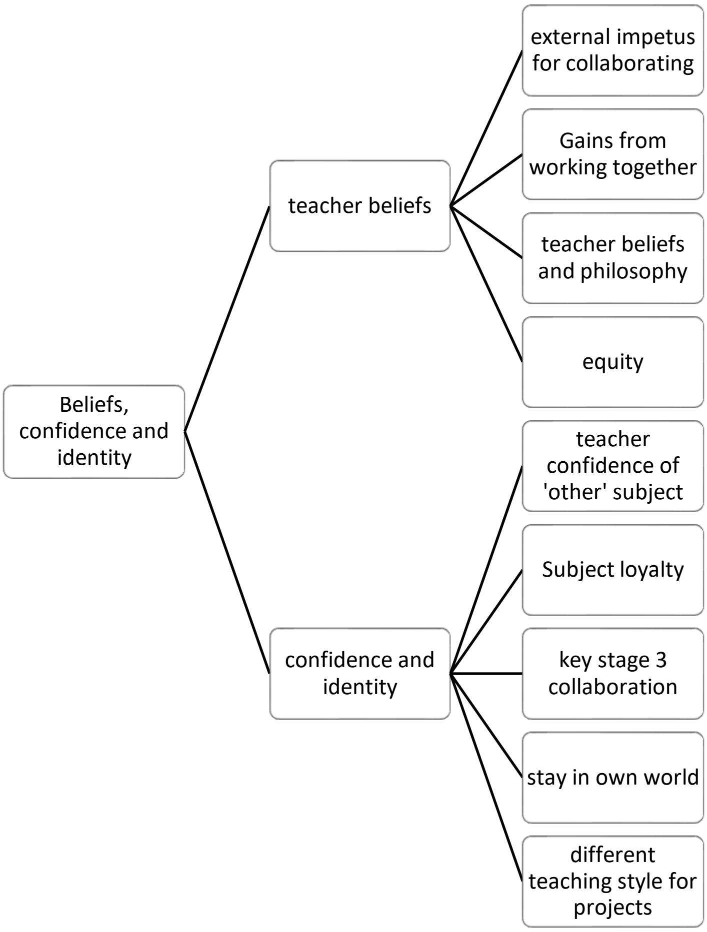

school practicalities
school collaboration is rare
social barriers
time
Leadership and staffing

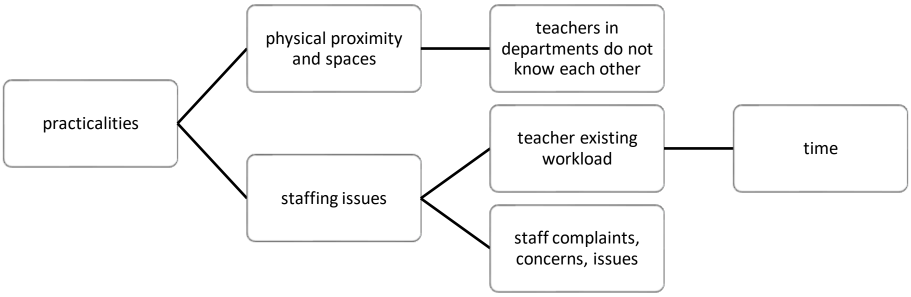
Schools coding tree






Use of maths in science
students making links
students don't see the links
students helped to see links
negative transfer
science as context
teacher knowledge of other
knowledge of other curriculum
knowledge of other pedagogy
examples of links
frustrations
mismatch in expectations
triangles
different setting
projects: not high level for subjects


Beliefs, confidence and identity
teacher beliefs
external impetus for collaborating
Gains from working together
teacher beliefs and philosophy
equity
confidence and identity
teacher confidence of 'other' subject
Subject loyalty
key stage 3 collaboration
stay in own world
different teaching style for projects


practicalities
physical proximity and spaces
teachers in departments do not know each other
staffing issues
teacher existing workload
time
staff complaints, concerns, issues

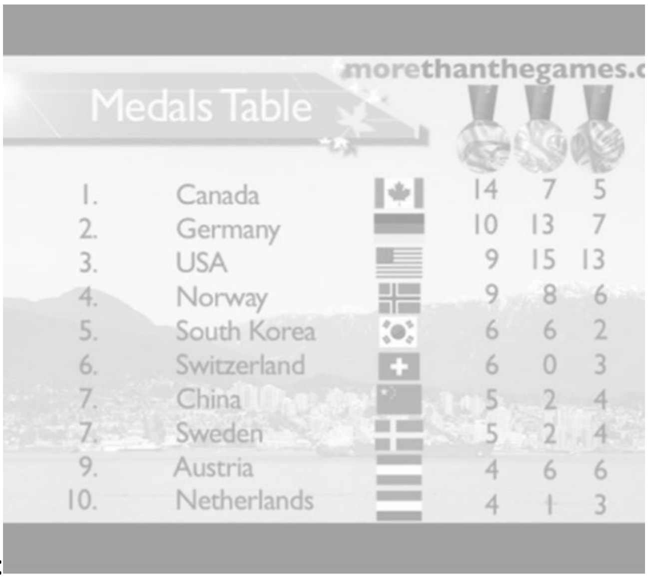
Appendix 10: Ceeton Practical Zone project

Practical Zone

Smoothie Challenge 2013

Subject: Maths
Name:
____

LESSON 1

Starter: 

1.	Canada	14	7	5
2.	Germany	10	13	7
3.	USA	9	15	13
4.	Norway	9	8	6
5.	South Korea	6	6	2
6.	Switzerland	6	0	3
7.	China	5	2	4
7.	Sweden	5	2	4
9.	Austria	4	6	6
10.	Netherlands	4	1	3

Write down 3 facts you have found from the table?

Writing a Hypothesis

What would the perfect smoothie be like? Reflect on the recipe, packaging, who might be the best person to represent you brand. Brainstorm your ideas.

Write your hypothesis about the sorts of things people want from their smoothies:

What could you do to improve your hypothesis?

Writing Good Questions

Write down what was wrong with the questionnaire questions below:
Now write 5 good questions that will help you answer you hypothesis:

LESSON 2

Collecting data from the class

Put your data collection tables below:

What went well with your collection tables? What did you have to improve? Write out your advice for what a good data collection table would have:

Good & Bad ways to collect data

Hypothesis	**Bad way to collect data**	**Good way to collect data**
Most students have school dinners for lunch.	Ask 10 students in the dinner hall queue at lunchtime	Randomly pick 5 students from each form group.
Football is the most popular sport in the UK		
The older you are the less time you spend on the internet.		

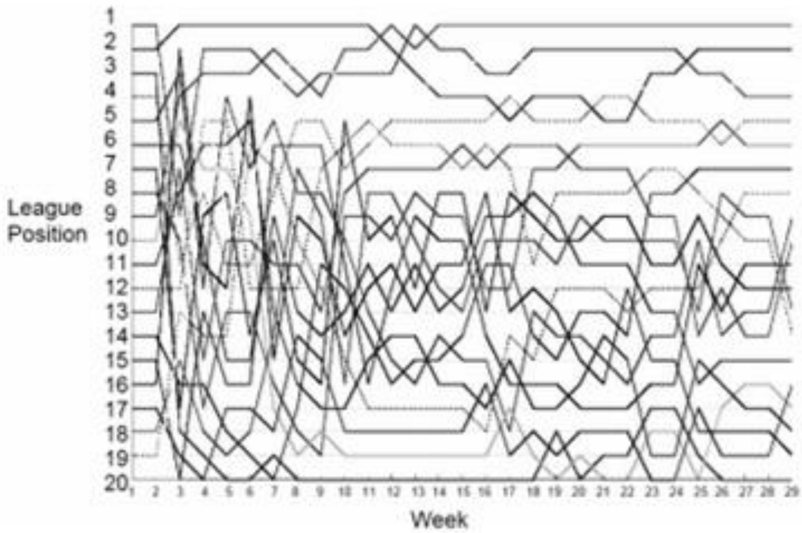
How you going to collect your data? You will need data from 20 students at least.

LESSON 3

STARTER

Scatter plot showing Federer's first serve landing points

League positions of teams in a football league during a season

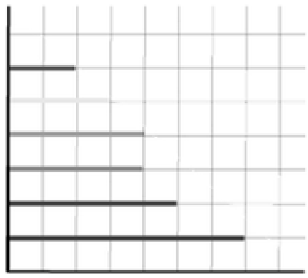


What did you work out from the diagrams on the other page?

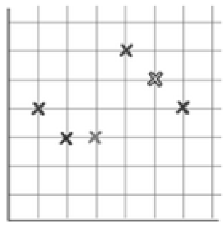
Looking at different types of diagrams

Look at the diagrams below. They all show the same data. Finish them off.

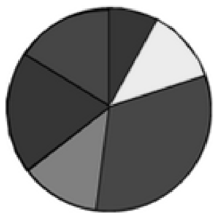
Here is Charlie's unfinished graph (he hasn't labelled anything yet):



Here is Tom's unfinished graph:



Here is Vincent's unfinished pie-chart:

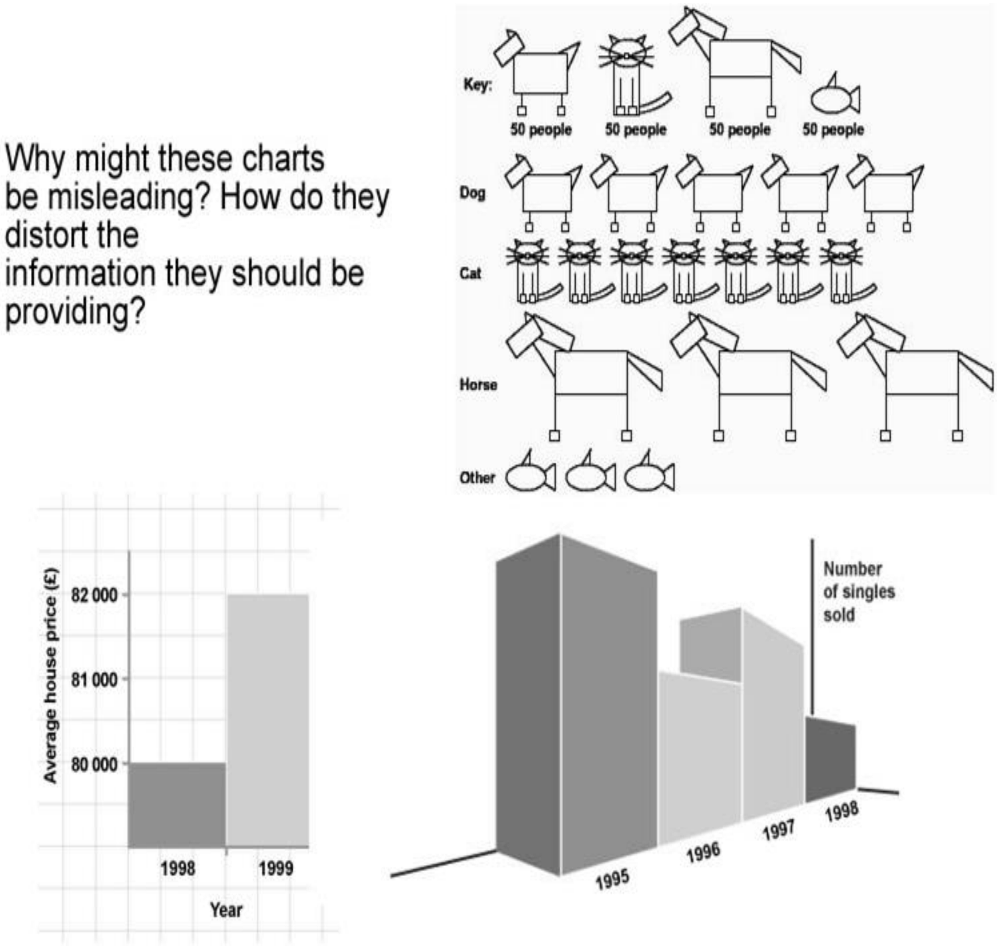


What is misleading about these diagrams?

What makes a good diagram?

For each of the diagrams above write down how you would produce a perfect example of one. What would you need to remember to include?

Misleading Diagrams



Write down all the reasons you think makes these diagrams misleading.

<u>LESSON 4</u>

Review of your project

Was your hypothesis correct? How do you know?

What went well in your project?

What could you improve in your project?

Conclusion

Science booklet from Ceeton

Practical Zone

Smoothie Challenge 2013

Subject: Science

Name:

____

Lesson 1

Burning food

Learning Objectives

- Recall the science classroom and lab rules
- Understand why we eat food
- Review the practical results
- Evaluate which energy value is best for which person

<u>Bingo</u>

Choose 9 of the following science lab statements and put each into a box on the grid.

Wear Goggles	Walk	Tie long hair back
Tuck your tie in	No running	No shouting
No eating	No Drinking	be careful
Planners out	Reports problems	put your hand up
Bags under desks	Check all equipment	Listen to teacher

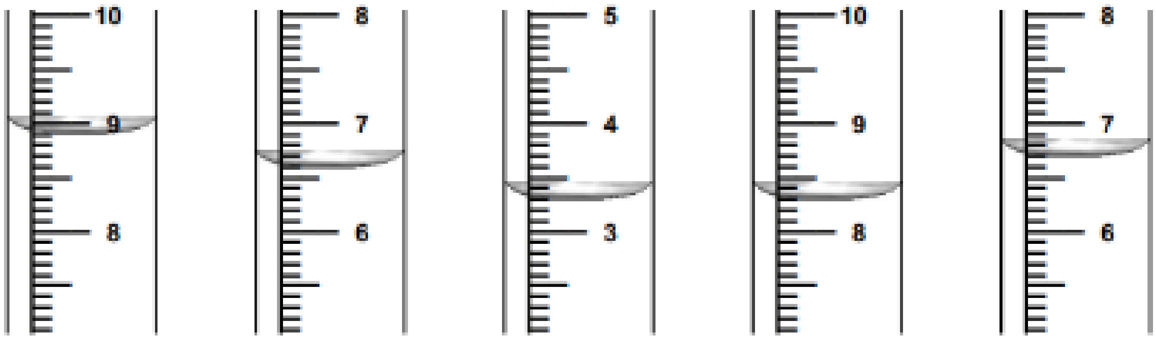
When you have got a correct answer you can cross it off your grid.

When all of them are crossed out you need to say

‘I AM THE SCIENCE MASTER AND I AM READY TO DO THE PRACTICAL’

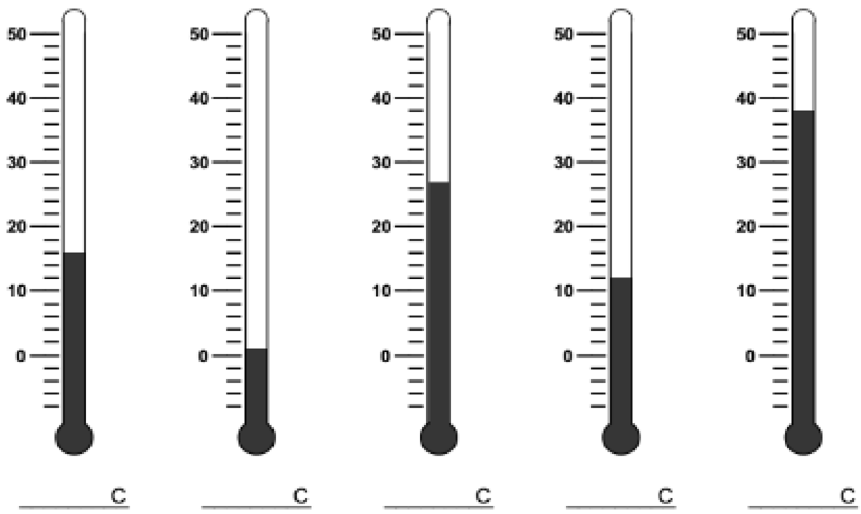
Skill that I need to use

<u>Reading the meniscus</u>



___________ ___________ ___________ ___________ ___________

Reading the thermometer



Lesson 2 Testing food

Learning Objectives

- Recall keywords carbohydrates, starch, fat and protein
- Understand why food tests are useful
- Review results from practical
- Evaluate food groups when playing top trumps

Bingo

Choose 9 of the following science lab statements and but each in to a box on the grid.

Carbohydrates	Sugar	Starch
Fats	Vitamins	Minerals
Water	Protein	Carrots
Peas	Chips	Pasta
Pizza	Egg	Chocolate
Haribo	Tomato	Birthday cake

When you have got a correct answer you can cross it off your grid.

When all of them are crossed out you need to say

'I AM THE SCIENCE MASTER AND I AM READY TO DO THE PRACTICAL'

Food Tests

Food or Chemical	Tested for… Protein, carbohydrates, starch or fats	Observation

Which food items contain starch?

Which food items contain carbohydrates?

Which food items contain protein?

Which food items contain fats?

Appendix 11: Deecom Hooke's Law Project

Year 8 Science and Maths Week

Name:

…………………………………………………………………………………

Maths teacher:

……………………………………………………………

Science teacher:

…………………………………………………………

2007

You will spend one lesson this week in science collecting some data, which you will write in this booklet. You will then spend a lesson analysing this data in Maths. We hope you enjoy it!

The Science and Maths Departments

The Science bit…

You are going to investigate how far a spring will stretch when you add masses to it.

Prediction:

……

……………

……

……………………………………………

Equipment:

Retort stand, boss and clamp

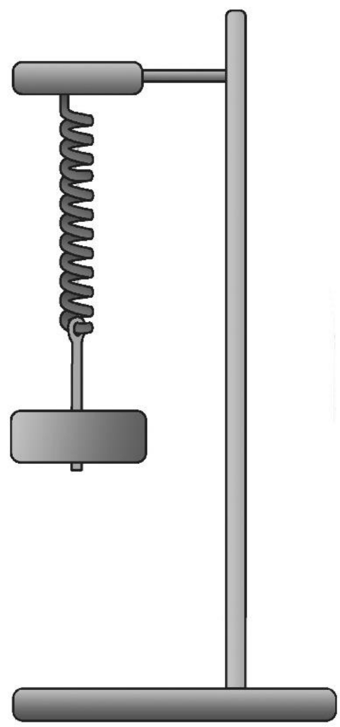
Spring

Masses and mass-holder

Ruler

Method:

1. Collect the equipment you need and set up the apparatus as shown in the diagram.
2. Record the length of the spring in millimetres with just the mass-holder on and write this in your results table.
3. Add one mass and record the length of the spring again in millimetres.
4. Repeat this until you have collected 'enough' data. Your teacher will talk to you about this before you begin.
5. Repeat the whole investigation another two times using the same spring.
6. IMPORTANT: Don't put too much mass on your spring or you will stretch it beyond its ability to spring back.



Results:

Mass (grams)	Spring 1 Length (mm)	Spring 2 Length (mm)	Spring 3 Length (mm)	Mean Length (mm)

Things to think about:

1. What is the difference between mass and weight?
2. Why did you repeat the experiment three times and calculate an average
3. What conclusion can you make from the evidence that you have collected?
4. How reliable is your evidence?

The Maths bit…

You are going to interpret the data you have collected in Science.

So far you should have a prediction and a table of results.

1. The first thing we need to do is to work out the mean of the three sets of you collected for each mass.

   We work out the mean by

   ………………………………………………………………………………

   ………………………………………………………………………………

2. Make sure you have filled in the "mean length" column in your table!

3. Now think about how we can interpret the data, using the techniques we have learn in Maths recently.

4. Carry out your interpretation (use the graph paper provided if you need to).

5. Use the space below to write about your findings:

Appendix 12: Deecom Year 8 Space Project

<u>Space Project – Meeting notes</u>

Week 1	Week 2	Week 3	Week 4	Week 5
Introduction to the project Group students (3 groups per class – x6) Set deadlines (presentation in week 4) Researching Planning Find resources Gathering information to investigate in week 3 - Continual assessment?		PSHE Week Space Museum	Compiling the presentation for Week 4	Presentations in the Hall - reflection time - judging Completion ceremony

The project aim: to answer the question 'What is Space?'

Each group will have to cover all of the following areas in their presentation to answer the above question

1) History and Exploration in space
2) Day & Night, Years & Seasons
3) Solar System
4) Moon & Satellites
5) Stars (including constellations)
6) Gravity

The presentation in week 4 can be in the form of a creative model, poster etc to contribute to the main question 'What is Space'.

During the final week Science teachers (who do not teach Year 8) can act as judges to assess the quality of work and help decide on passing the Bronze Crest Award.

Time needed for reflection in class on what went well, ways to improve the project then feedback to the staff involved.

Learning objectives
Space Project

1) History and Exploration in space
- Describe some different ways in which scientists can find out about the Solar System
- Evaluate the advantages and disadvantages of some of these methods

2) Day & Night, Years & Seasons
- Recall the lengths of days, months and years
- Describe a model which explains why we have days, nights and years
- Describe what a satellite is
- List the difference between summer and winter in Europe
- Use a model to explain that we have seasons because the Earth is tilted
- Recall that the northern hemisphere is tilted towards the Sun in the summer

3) Solar System
- Describe how planets, dwarf planets and asteroids are arranged in the Solar System
- Explain why planets look brighter than stars

4) Moon & Satellites
- Explain how we can see the Moon
- Explain why the shape of the Moon seems to change as it moves around the Earth
- Use a model to show the arrangement of the Sun, Earth and Moon during a solar eclipse and lunar eclipse

5) Stars (including constellations)
- Describe what a star is and why we can only see them at night
- Use a model to explain why the stars appear to move across the sky
- Explain what the words constellation, galaxy, Milky Way and Universe mean.

6) Gravity
- Explain the differences between mass and weight
- Recall factors that affect the strength of gravity
- Describe how gravity can affect planets, moons, stars and spacecraft

Appendix 13: Eyston Mathematics and science policy

Science and Mathematics Departments

Areas of common concern: We have agreed upon the items below. Please be consistent in your usage.

Equipment

This is a protractor, not an angle measurer

This is a pair of compasses, not a compass.

Mass and weight
Science staff should be aware that in Mathematics 'weight' is often measured in units of kg or g. Mathematics staff should be aware that in Science, mass is the quantity of matter in an object and is always measured in kg or g. Weight is the force of a gravitational field upon an object and is always measured in N.

Averages
Science staff should use the term 'mean' rather than 'average' when requiring the arithmetic mean of a data set. If the textbook or worksheet states 'average' Science staff must make it clear the mode or median is not required.
Mathematics staff need to be aware that in Science the word 'average' nearly always refers to the mean.

Calculations
Science staff should be aware that mental arithmetic skills are encouraged in Mathematics. For KS3 in particular, simple calculations should be done without a calculator where possible.
Full working out should always be shown for Mathematics and Science.
The = must be used correctly.
E.g. 7+3 = 10 10 +2 = 12 NOT 7+3=10+2=12
Science staff should make clear the number of significant figures or decimal places required for calculated answers.

Data tables
Units must be present in the column headings only not in the data cells.

Graph drawing
Points on graphs should be plotted as a +.
Science staff should say 'scatter graph with line of best fit' rather than 'line graph'.
Science staff should be aware that 'bar graph' and 'histogram' are not the same thing.
(Follow this link for a reminder about the difference. http://stattrek.com/statistics/charts/histogram.aspx)
Mathematics staff should be aware that experimental data rarely falls on the best-fit line. Science staff should be aware that in Mathematics the data generated from plotting e.g. y=mx+c always falls on the best fit line. This can lead to confusion for pupils.